Handing multiple communications sessions in an heterogeneous network environment

Master of Science Thesis

RODRIGO ALBERTO VACA RAMIREZ

Department of Signals and Systems
Division of Communications Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2009
Report No. EX101/2009

Handing Multiple Communications Sessions in an Heterogeneous Network Environment

Rodrigo Alberto Vaca Ramirez

Examiner: Erik G. Ström

Advisor: Victor M. Ramos Ramos

Advisor: Mohammad Reza Gholami

Department of Signals and Systems

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden EX101/2009

To my family who always support me with great love.

Abstract

The coexistence of several wireless networks composed for a set of different technologies has become an imminent fact for the next generation of wireless networks. These technologies exhibit different kinds of jitter, delay, bandwidth, coverage and power consumption, which impose new challenges on mobility management so as to keep the users best connected to available access networks. Mobile users experiment handoff events while moving within a wireless network. The handoff decision was traditionally based on the evaluation of the received signal strength (RSS). However, when vertical handoff occurs, the RSS comparisons are not enough to perform the handoff decision, since such scheme does not take into account the different network conditions. In order to address some of this challenges the IEEE 802.21 Media Independent Handover (MIH) Service Work Group is working on a standard for handovers without being tided into the features or specifics of particular wireless technologies. The main goal of this standard is to provide interoperability among heterogeneous networks including different technologies (eg. WiMax, WiFi, UMTS, GSM) improving the user experience of mobile terminals. A mobile node equipped with multimedia-enabled wireless devices will be expected to use real-time and non-real time applications at any time anywhere from diverse networks. Furthermore mobile nodes are expected to conduct multiple communications sessions at the same time. For this case, the handoff can be optimized collectively or individually for each session. Therefore, a balance between the different QoS requirements for each session has to be made among the conflict decision results. In principle this is a problem of group decision making and it must be treated as a probabilistic issue.

We present in this work a novel solution to the problem of vertical handoff for wireless networks when a mobile node carries multiple communication sessions with different QoS requirements. We solve this issue by treating it as a group decision making problem. We extend the classical AHP (Analytic Hierarchy Process) method to provide the mobile node with two types of solutions: a deterministic solution and a probabilistic one. The method we propose provides the mobile node with a wider range of parameters so as to make a more accurate decision when handing off to a different network.

KEYWORDS: VERTICAL HANDOFF, IEEE 802.21

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 An overview of the next generation of wireless networks

The coexistence of several wireless networks composed for a set of different technologies has become an imminent fact for the next generation of wireless networks. These technologies exhibit different kinds of jitter, delay, bandwidth, coverage and power consumption, which impose new challenges on mobility management so as to keep the users best connected to available access networks. Mobile users experiment handoff events while moving within a wireless network. The handoff decision was traditionally based on the evaluation of the received signal strength (RSS). However when vertical handoff occurs, the RSS comparisons are not enough to perform the handoff decision. Since this decision scheme does not consider the current network conditions (eg. bandwidth, jitter and delay).

In order to address some of this challenges the IEEE 802.21 Media Independent Handover (MIH) Service Work Group is working on a standard for handovers without being tided into the features or specifics of particular wireless technologies. The main goal of this standard is to provide interoperability among heterogeneous networks including different technologies (eg. WiMax, Wi-Fi, UMTS, GSM) improving the user experience of mobile terminals.

A mobile node equipped with multimedia-enabled wireless devices will be expected to use real-time and non-real time applications at any time anywhere from diverse networks. Furthermore mobile nodes are expected to conduct multiple communications sessions at the same time [1]. For this case, the handoff can be optimized collectively or individually for each session. Collectively means that all the communication sessions are handed off to the same target network and individually that each user's session can be handed off to a different target network. When all sessions are optimized collectively it should be considered that each traffic class has different QoS requirements based in delay, jitter, bandwidth and (Packet Error Rate) PER during the handoff decision process [2]. Furthermore, a balance between the different QoS requirements for each session has to be made among the conflict decision results.

In our proposal we conceive the handoff decision making problem as a probabilistic issue in order to consider a mobile node carrying multiple communication sessions. A tradeoff between the different QoS requirements is established for each service class to model this issue as a group decision making problem [3], [4].

1.2 Handover issues

Handoff is the procedure of maintaining the active connections when a mobile node switches from an access network to another. Furthermore handoff can be divided in two types, based in the kind of network environment where handoff is performed; horizontal and vertical.

Horizontal handoff is a handoff between two network access points that use the same network technology and interface (homogeneous environment) [5]. For example when the handoff is performed between 802.11b network domains, it is considered as horizontal since the connection is disrupted only by the change of 802.11b domains and no by the change of technology. Horizontal handoffs are performed when the access router becomes unavailable due to mobile node movement across the network. Traditionally the handoff of research for an homogeneous environment has been based on the evaluation of the received signal strength. Since the capabilities of each network based on the same kind of technology are the same and the determinant parameter which trigger the handoff is only the RSS.

Vertical handoff occurs when the mobile node moves through different technology networks (heterogeneous environment) [6]. For example when the mobile node moves from a 802.11b network to a UMTS network the handoff event is considered as vertical.

Furthermore vertical handoffs can be divided in: down handoffs which are from a low coverage and faster network to an extended and slower one (eg. WLAN to and UMTS network). On the other hand up handoffs are defined as the opposite case.

Vertical handoffs are performed when the current network is overlaid which is a common situation in heterogeneous networks [6]. Hence the handoff can be initiated by convenience rather than by connectivity reasons. The effectiveness of vertical handoff is based on the mobile's node movement detection and the capability of detecting that the current access networks will become unavailable before it actually does.

Some examples are the following [6]:

- The Ethernet cable has been unplugged but there is an active wireless network connection available.

- The wireless signal from 802.11 is becoming weaker but there is an active connection detected in the 3G data card.
- There is an active 802.11b connection but a high speed connection becomes available in another channel through a different access point.
- There is an active connection in the 3G card, however a higher speed 802.11 connection has become available.

Handoff can be categorized based on the configuration and signaling handshake. If the configuration and signaling steps are made before the mobile node leaves the current network, handoff is called make *before brake* (or soft handoff). When the opposite case occurs it is called *brake before* made (or hard handoff).

Soft handoff maintains the connectivity of all the applications on the mobile node when the handoff occurs. Its aim is to allow continuous end to end data services when link outages of handoff events occur [7].

1.3 Motivations

The main characteristic of the next generation of communications systems (eg. 4G) will be a composite communication model. Where a different kind of technologies such as cellular, satellite and Wireless Local Area Networks and wired networks will interact to provide an optimum service at any time from anywhere to the mobile node. One of the popular current issues for heterogeneous environments is the integration within WLAN and cellular 3G systems [8]. Cellular networks as General Packet Radio (GPRS), Universal Mobile Telecommunication Systems (UMTS) and CDMA 2000 support a low bandwidth over a high coverage. On the other hand systems as WLAN and HiperLAN/2 provide a high bandwidth (up to 54 Mbps) for a small coverage area. Therefore the integration of WLAN and cellular systems can efficiently achieve a suitable capacity and QoS for the mobile node.

All these networks technologies differ in bandwidth, latency, power consumption and potentially in their charge model. The issue is how to integrate these seamlessly.

In addition, dynamic factors should be considered in handoff decision for effective network usage. Furthermore information of actual networks conditions can help load balancing across the networks; current user conditions, such as mobile host's moving speed can eliminate certain networks for consideration (eg. networks which cannot support mobility). Available hints like user activity patterns and network coverage can also contribute to handoff decision.

Hence a handoff decision engine should be considered in order to maintain the main goal of mobility: seamless. To achieve it, the handoff latency should be low enough to disrupt the running applications. However this issue has been addressed before in [9]. Furthermore the automation of switching from one network to another is based in the principle of minimal interaction from the user side. User involvement is required for the development of the handoff decision engine. Hence minimal user interaction means automation. The handover decision engine should be based on a simple and intuitive process, otherwise the user will manually configure the networks violating the aim of seamless.

Furthermore in order to address some of these challenges, the IEEE 802.21 is emerged to address seamless handover in homogeneous and heterogeneous environments. Information collection and exchange can be performed by the Media Independent Handover (MIH) Services. The IEEE 802.21 only provides the capability and possibility which allows the mobile node to select a suitable network to handover. However IEEE 802.21 does not have defined the way of how the networks selection process should be performed. On the other hand most of the network selection algorithms base their decision in a single criterion. However this kind of decision cannot provide the correct performance in a highly integrated platform [10]. Hence a wide range (multi-decision criteria) of network parameters should be taken in consideration to achieve better performance and more pleasant user experience.

In the next generation of wireless networks a mobile node equipped with multimedia-enabled wireless devices will be expected to use real-time and non-real time applications at any time anywhere from diverse networks. Furthermore mobile nodes are expected to conduct multiple communications sessions at the same time (eg. voice, video or file downloading). Hence when the mobile node handoffs to a new target network all the communications sessions should be optimized collectively based in the different QoS requirements, in order to handoff to the network which offers the best QoS for all the applications sessions.

In this work we propose a handoff decision algorithm which considers the tradeoff within the different QoS requirements for all communication sessions and the variant conditions of each target network. We use the AHP (Analytic Hierarchy Process) to provide the mobile node with two kinds of solutions, a deterministic solution which provides the rank of the target networks and a probabilistic one which gives the probability that this ranking remains stable [6].

1.4 Contributions

The following are the major contributions of this thesis work:

1. A study of the evolution of wireless communication systems and the identification of handover related issues for the next generation of wireless networks.

2. A survey and comparison of current handoff decision algorithms in a heterogeneous environment.

3. In this work we present a novel solution for the problem of a mobile node carrying multiple communication sessions with different QoS requirements and needs to execute handover to a different network. This issue has been treated as group decision making problem. Our algorithm takes in consideration the tradeoff within the different QoS requirements for both communication sessions and the variant conditions of each target network.

4. We apply an extension of the classical AHP method in order to provide the mobile node with two kinds of solutions: a deterministic solution based in the traditional AHP method and a probabilistic solution. The first solution provides the mobile node with information due to the ranking of the target networks and the second one the probability that this ranking remains stable considering the uncertainty into the comparison judgments. This method provides the mobile node with more parameters to make a more accurate decision when handoff is needed.

Chapter 2

Related Work

2.1 Evolution of Wireless Communications

The first-generation (1G) of communication systems based on analog FM transmission for speech devices was introduced on early 1980s. Some examples are the Advance Mobile Phone Service (AMPS) which used FDMA/FDD and the Nippon Telephone and Telegraph (NTT). A cellular cell covering area (eg. 130 km) was supported by a single base station [15].

1G systems support roaming and handover capabilities. However cellular networks are unable to operate within countries since cellular systems are incompatible. Another disadvantage is that there is not control power mechanism in 1G networks. Therefore the mobile node and base stations transmit at high power making the communication impracticable.

Most of today's ubiquitous cellular networks use what is commonly called second generation or 2G technologies which conform the second generation of cellular standards. The second generation standards use digital modulation formats, and multiple access techniques (eg. TDMA/FDD CDMA/FDD) [16]. 2G standard supports low bit rate and conventional voice services.

The most popular second generation standards include three TDMA standards and one CDMA standard: Global System for Mobile communications (GSM), Interim Standard, Pacific Digital Cellular and cdmaOne respectively. These standards represent the first set of wireless air interface standards to rely on digital modulation and sophisticated digital signal processing in the handset and the base station.

One of the main advantages of this 2G standards is the notion of frequency reuse which was introduced in order to increase the system capacity. Frequency reuse stands that frequencies and channels can be reused within communications systems to improve capacity and spectral efficiency as it is shown in Figure 2.1. Hence two transmissions can employ the same frequency if there are far enough away such that the co-channel interference level is below a desired threshold.

The 2G standard was widely deployed by wireless carries for cellulars and Personal Computer Systems (PCS). This standard was designed before the widespread use of the Internet [15]. Hence 2G technologies use circuit-switched data modems which limit data users to a single circuit-switched voice channel. Furthermore all 2G networks only support single user data rates on the order of 10 kbps. Such speed is too slow for Internet applications.

However the 2G standard was able to support limited Internet browsing and sophisticated short messaging capabilities. For example Short Messaging Service (SMS) is a popular feature of GSM, which allows the user to send real-time messages to other subscribes over the same network.

In an effort to provide high data rates in order to support Internet applications, new data-centric standards have been developed. These standards represent 2.5 technology and allow existing 2G equipment to be modified to support higher data rate transmissions for Internet applications (eg. web browsing, e-mail traffic and mobile commerce.)

Third generation systems (3G) offer a significant increase in capacity and is the most suitable system for broadband data access. 3G systems include wide-band mobile multimedia networks and broadband mixed wireless systems [17]. 3G developers envision mobile nodes with the possibility to receive live music, conduct interactive web sessions and have simultaneous voice and data access with multiple parties at the same time from the same mobile node. The mobile systems support different data rates based in the level of mobility. For example 140 *kbps* is supported for full vehicular mobility and higher bandwidths for pedestrian levels of mobility. There are three primary standards which comprise the 3G systems: wide band code division multiple access (W-CDMA), CDMA 2000 and time-division code multiple access [15]. Some of the main advantages of 3G systems are: the Multi-megabit Internet access, communications using Voice over Internet Protocol (VoIP), voice-activated calls and unparalleled network capacity.

Beyond 3G incorporates two essential concepts: the first is the improvement of data rate transmission with data rates of 100 *Mbps* while mobile and 1 *Gbps* while stationary [17]. Furthermore in 4G networks a mobile node is expected to support many access technologies (eg. UMTS, GSM, Wi-Fi) with simultaneous and smoothly transitions between them. For example it is easy to support high data rates in a Wi-Fi network that in a WiMax network. However due to its high coverage a WiMax network can support mobility better than a Wi-Fi network.

Two technological advances that allow the mobile node to experiment high data rates are the key of the evolution of wireless networks. One of them is the orthogonal frequency division multiplexing (OFDM), where a large number of closely-spaced orthogonal subcarriers are used to carry data. The data is divided into several parallel data stream or channels, one for each subchannel. OFDM reduces the impact of fading since symbols are spread over relative long periods of time. The other advance is multipleinput multiple-output (MIMO). MIMO offers significant increases in data throughput and link range without additional bandwidth or transmit power. This technology relies on multipath to send multiple versions of several bit streams by multiple antennas.

Another important issue for the migration to 4G is the development of an appropriate handoff decision engine which improves the performance of this integrated system. The new network environments complicate the issue of handover, since the convergence in heterogeneous networks leads to the problem of frequent handovers [10]. Therefore an effective and accurate handover decision engine is needed in order to switch the mobile's node sessions from the current network to the network which offers the best QoS for mobile node applications, when subscriber is moving through the network.

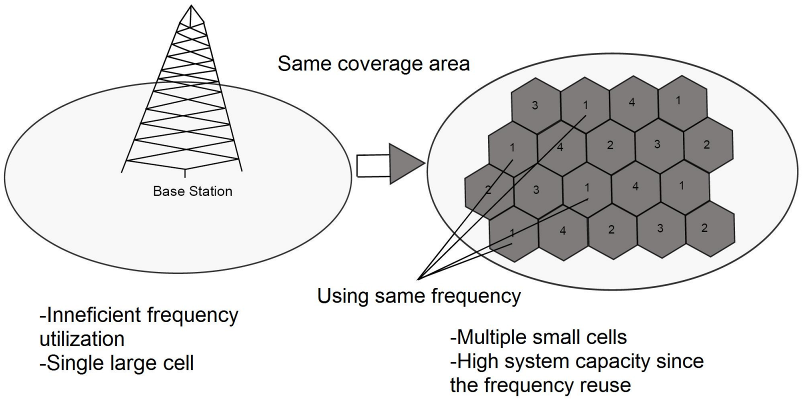

Figure 2.1: Comparison between first and second generation systems based on frequency reuse

2.2 Handover Process

The handover process is divided in the four following steps shown in Figure 2.2: handover initiation, handover pre-selection, handover preparation and handover execution.

Handover Initiation: The mobile node starts handoff since the network's conditions has changed or the mobile node is moving away from the network coverage and it is entering to the area covered by other network. All the communications sessions should be transfered to new target network in order to provide a suitable QoS for the user. When handoff starts the mobile node starts searching for new links. After network discovering the mobile node will select the most suitable network based in certain criteria.

Handover Pre-selection: The aim of this stage is to screen out unsuitable candidate networks for consideration before the mobile node starts measuring the signal strength and retrieve the capability information from candidate networks. For the pre-selection, the mobile node can use user defined policies and also consider network's constrains. Therefore the number of candidate networks can be reduced considerably.

Handover Preparation: It is performed when the mobile node has chosen the more suitable network to handoff. A new link between the mobile node and the base station is set up in order to provide connectivity and protocols for layer 2 and layer 3.

Handover Execution: After the new link is established between the mobile node and the base station. All the communication sessions associated with the old link are transmitted to the new one. The control signals and data packets are allocated into the new link.

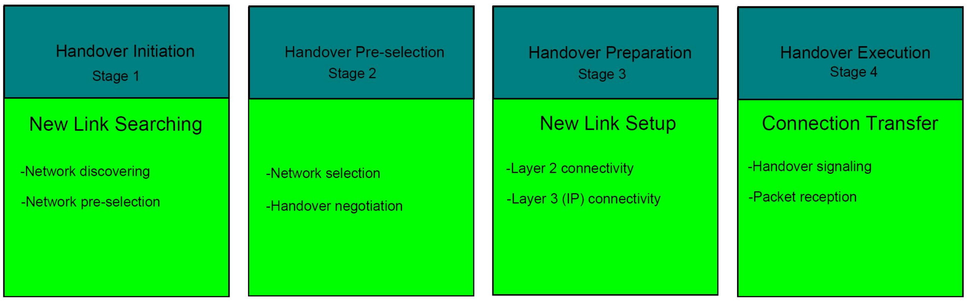

Figure 2.2: Handover Process.

2.3 Literature Survey

In [23] the authors propose a vertical handoff decision algorithm which considers the combined effects of Signal to Interference plus Noise Ratio (SINR) from different access networks as the handoff criteria, which provides the knowledge of the achievable bandwidths from both access networks to make the handoff decision considering QoS. However the approach used in [23] only considers maximum achievable bandwidth as decision criteria without considering the current condition of the target network. Hence in order to take an accurate decision to provide the best QoS for the application session, other criteria parameters as cost, jitter and delay should be taken in consideration [27].

The authors of [24] propose a vertical handoff scheme which uses the Grey Prediction Algorithm (GPA) to calculate the predictive signal strength, which can tell when to start a handoff. Furthermore a Quantitative Decision algorithm based on fuzzy logic is proposed. This algorithm takes three QoS parameters, received signal strength (RSS), available bandwidth and monetary cost of target networks as decision criteria. Hence the final decision is made comparing the quantitative decision values of each candidate network. However methods based on fuzzy logic are cumbersome to use which require much expert knowledge and user involvement in order to make decision rules.

The author of [3] address the handoff trough heterogeneous networks as a fuzzy Multiple Attribute Decision Making (MADM) problem for which fuzzy logic is used to deal with imprecise handover criteria and user preference. The author makes a comparison and analysis for different decision methods. Furthermore he proposes a new method to solve this problem. First handover decision data is converted to crisp numbers, then classical MADM methods like Simple Additive Weighting (SAW) and TOPSIS are applied to obtain the rank of the networks. The approach used in [3] is one of the first which addresses the handoff decision as a MADM problem. Although the preference on handover criteria for the running applications is modeled as weights assigned by the user on the criteria. Furthermore to obtain realistic results handover decision should be based on utility instead of using criteria directly.

In [5] a handoff decision scheme is proposed to select the best suitable network based on the mobile required parameters. The calculation task is performed by the target networks. The decision making is formulated as a MADM problem which is an evaluation of a set of alternative networks. In [19] a MADM handover decision algorithm is proposed for WiMAX and Wi-Fi networks, where the Analytical Hierarchy Process (AHP) is used to calculate the weights of various traffic parameters and the Simple Additive Weighting (SAW) or Multiplicative Exponent Weighting (MEW) are applied to calculate the QoS score function.

The work done in [5, 19] conceives the handoff as a decision making process. However these papers address the handoff decision problem as a deterministic issue. Therefore in both cases the handoff decision is based on the requirements of an active communication session. Hence there is no need to establish a tradeoff within the session requirements for the decision making process.

In [22] the authors propose a framework to perform handover. This framework relies over a decision model in order to handover to the best wireless interface at the best moment. The decision is done in two stages: in the first stage the user specifies which specific devices should be removed from the candidate list to avoid undesirable interferences to other devices inside the area. In the second stage information for each network interface is retrieved. Furthermore the decision is taken based in a score function which considers usage expense, link capacity and power consumption. An important part of the approach taken in [22] is the introduction of a preselection process to which removes certain networks from the candidate list based in a specific criteria.

In [20] a policy enabled handoff mechanism which allows users to express policies to decide the best wireless system at the current time is proposed. This scheme considers the network dynamic factors (eg available bandwidth, network latency) and parameters with fixed budgets (eg. network's cost and power consumption) for the decision making. To perform this task a cost function is proposed which considers available bandwidth, cost and power consumption as parameters. The network with the lowest calculated value of the cost function will provide the most benefit to the user. Furthermore this scheme considers an stability period which is defined as the waiting period before handoffs in order to handover to the best consistently network to avoid the ping pong effect. Where the ping pong effect is the phenomenon experimented when the current conditions of the neighboring networks change suddenly. Therefore when handoff is executed to a new target network, there is a high probability that the mobile node experiments handoff continuously within the neighboring networks. To manage the issue that several mobile nodes execute handover to the same network at the same time, a random waiting time within the stability period is proposed. The approach proposed in [20] is one of the firsts which considers a handover policy for heterogeneous networks. However the main disadvantage is that handoff decision is based in a simple score function. Furthermore the weights of the criteria parameter are obtained from the user, which means that this algorithm needs user involvement and interaction for the correct performance.

In [21] the vertical handoff decision problem is modeled by a cost function, which depends on the cost of receiving each of the user's communications sessions to the target network. The network choice with the lowest calculated value for the cost function will provide the most benefit for the user. This approach addresses the problem of a mobile node carrying multiple communication sessions. It considers two cases: In the first case the handoff decision is optimized collectively, which means that all the sessions are handed off to the same target network. In the second case the handoff decision is optimized individually for each communications session which means that each session is handed off to a specific target network. The main disadvantage of this approach is when the handoff decision is made collectively, the score function does not consider the tradeoff between the different QoS requirements for each communication session. Therefore the proposed solution cannot provide the adequate QoS for the mobile node applications.

In [31] we have proposed a novel method which allows the mobile node to handoff to the more suitable target network, when it carries multiple communications sessions. The proposed method provides the mobile node with the more appropriate QoS requirements. Our algorithm has the same properties of the algorithm exposed in [19], both algorithms are multidimensional which allows them to considered different QoS requirements. However our method is based in an extended version of the AHP. Therefore it is possible for this novel handoff decision algorithm to consider the tradeoffs between the different the QoS requirements for the different communications sessions. Since in [31] the handoff decision is conceived as a probabilistic process instead of a deterministic one as it was considered in [19]. In this work we have compared too the basic RSS scheme with our proposed method. Since it is well known that the RSS scheme does not performs well in heterogeneous environments. However we have used the RSS method as a base line for comparison.

Chapter 3

IEEE 802.21: Media Independent Handover Services

To address the challenges imposed by the mobility management within heterogeneous networks, the IEEE 802.21 Media Independent Handover (MIH) Service Work Group is currently working on a standard for handovers without being tided into the features or specifics of particular wireless technologies. The IEEE 802.21 [30] provides a new protocol layer: the MIH layer (between data link and network layer) which works as a generic interface for the interaction between different lower layer technologies and the upper layers, hiding the technology-specific primitives. To manage particularities of each technology MIH defines a set of service access points (SAP) to gather information and control link behavior during handovers. Furthermore the IEEE 802.21 defines a group of network-network and network-terminal interfaces in order to transport information stored at the the service provider's network to an appropriate location.

The main functionality of 802.21 is contained in a set of MIH services: Event, Command and Information which provides as key benefits optimum network selection, seamless roaming to maintain connections and lower power operation for multiradio-devices.

3.1 IEEE 802.21 objectives

The 802.21 is centered to achieve the following primary goals:

- Providing a framework that enables seamless handover between different wireless technologies (WIFI, GSM, 3G, UMTS). This framework should allow the necessary interactions within devices for optimizing the handover performance.

- Providing a common interface for link layer functions which must be independent of the specific particularities of each technology.

- Providing handover enabling functions which gives the possibility to the upper layers to perform the handovers.

Since the purpose of IEEE 802.21 is to enable handover between heterogeneous networks a set of secondary goals should be defined in order to pursue this issue:

- Service continuity during and after handovers.
- Handover-aware applications. The 802.21 should provide applications with functionalities to participate in handover decisions.
- QoS-aware handovers. The 802.21 should provide the necessary functions to handover to the network which supports the desired QoS.
- Provide the mobile node with information of the available candidate networks to handover.
- However the handover decisions are left to upper layers. The 802.21 should provide the necessary functions to assist the network selection process.

The IEEE 802.21 architecture is core centered in the Media Independent Handover Function (MIHF). Its main task is to coordinate the information exchange between the different devices involved in the handover procedure. MIHF acts as an intermediate layer allowing the interaction within upper layers and lower layers. The MIHF framework has a set of users (upper layers) which employ it to control and gather handover-related information Figure 3.1. This figure shows a common logical diagram of the different entities involved in the handover procedure. Furthermore, it shows a mobile node with two interfaces, a 802 interface and a 3GPP interface, the mobile node it is actually connected to the 802 network and will execute a handover to the 3GPP network. However similar diagrams can be used in order to explain the interaction within technologies as Wi-Max, Wi-Fi or UMTS. The information exchange between upper layers-MIHF-lower layers is done mainly by a set of services access points (SAP). The SAPs contained in the IEEE 802.21 are the following:

- MIH-SAP: This interface allows the information exchange within the MIHF and upper layers.
- MIH_LINK_SAP: This interface allows the information exchange within the lower layers and the MIHF. Furthermore the MIH_LINK_SAP has been defined to be common to all technologies, so the MIHF is independent of technology-specific primitives.
- MIH_NET_SAP: This interface allows the information exchange within MIHF situated in different entities.

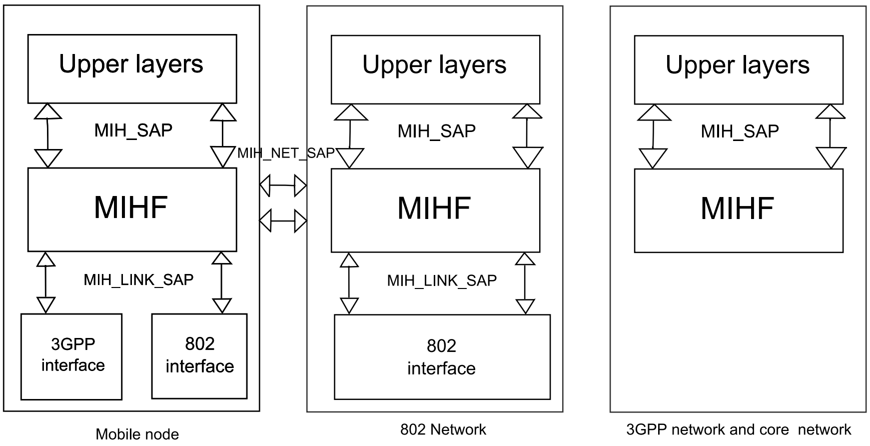

Figure 3.1: 802.21 Architecture [30]

3.2 MIH services

The IEEE 802.21 defines three different types of services which allow higher layers to access information for a more effective handover decision and deliver commands to the link and network layers. Furthermore the information transmitted for the link layer to the upper layer is delivered asynchronously while commands generated in the upper layers are delivered synchronously. The MIH services are divided in:

- Event Services (ES)
- Command Services (CS)
- Information Services (IS)

3.2.1 Media Independent Event Services (MIES)

Events related to handover can be originated from MAC, PHY and MIHF either at the mobile node or at the point of attachment to the network. The IEEE 802.21 provides two kinds of handover based on control model: terminal initiated handover and network initiated handover. The main difference between these models is the entity that controls the handover process. MIES indicate and predict dynamic changes in the state and behavior of the physical and data link layers to the upper layers, since these changes can trigger immediate handoffs decisions. In order to receive the event notification from the MIHF the upper layers must perform a registration; when an event is generated it will be delivered only to the entities that were previously subscribed to it. MIES can be divided in link events and MIH events. Link events are generated in lower layers and propagated to the MIHF some of these events can be propagated to the upper layers becoming MIH events. MIH events are propagated from the MIHF to the upper layers as it is shown in Figure 3.2.

The MIES types are:

- State change events: The main purpose of these event types is to inform about a current change in the PHY or MAC state (Link up, Link down) or when a prespecified link parameter has changed its status (Link Parameters Change). State events as Link Detected indicate that a new link has become available giving the possibility to perform a handover based on the radio link conditions of this new link.
- Predictive events: These events inform about a possible future change in the PHY or MAC conditions (Link Going Down).
- Link Synchronous events: These events provide information about the current handover state (Link Handover Imminent, Link Handover Complete).

To summarize MIES are useful to detect when a handover is possible or necessary, due to the changes in the radio link conditions.

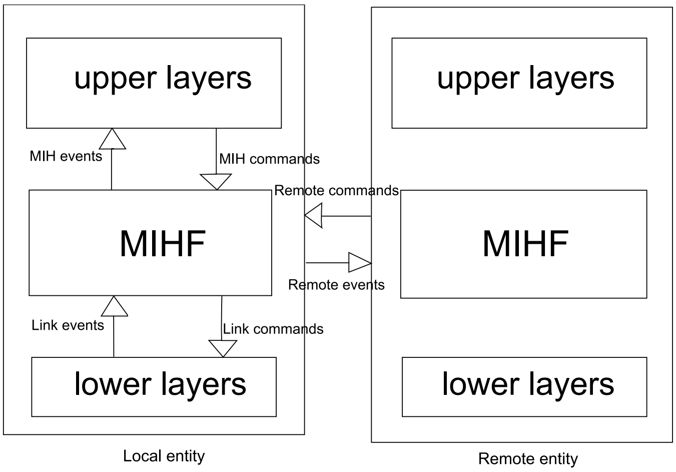

Figure 3.2: 802.21 Event command and information services flow mode

3.2.2 Media Independent Command Services (MICS)

MICS are the commands sent from the upper layers to the lower layers in order to gather link status information as well to apply mobility and connectivity decisions to improve the handover performance. The mobility management protocols incorporate dynamic information as link status parameters and static information like current network status and network's operator. To help the mobile node during the decision making process.

The Media Independent Commands can be delivered locally or remotely. For the commands delivered remotely the network will force the handover process on the mobile node allowing the use of network initiated handover control model. As it is shown in Figure 3.2 the MICS are sent from the upper layers to the MIHF and from the MIHF to the lower layers.

Commands are classified in two main categories:

- MIH commands: These commands are sent from the higher layers to the MIHF to help during the handover process. Furthermore MICS provides a important set of commands which helps in the decision making. As the MIH handover initiated and MIH handover prepare.
- Link commands: These commands are generated in the MIHF and sent to the lower layers in behalf of the MIH users for management and configuration.

3.2.3 Media Independent Information Services (MIIS)

In order to migrate from the current network to a new network, the MIIS provides a framework through which the MIHF located in the mobile node or the network can gather information to discover the capacity of the target networks within a geographical area of interest to optimize the handover procedure when the mobile node is roaming across these networks. In the decision making process the mobility management protocols should consider dynamic information provided by the MIH events, static information provided by the MIIS and command services explained earlier. Static information may include names of the network providers, neighbor maps and coverage zones. While dynamic information includes channel information, security information and MAC addresses [30]. All this in order to do an effective handover decision. It is important to notice that information related to the heterogeneous networks presented in an specific area can be accessed for any single technology interface presented into the mobile node. As an example a mobile node connected to a UMTS networks, can gather some information about a GSM or WIFI network within its geographical area without the need to turn on the GSM or WIFI interface in the mobile node providing a more efficient power utilization.

The main goal of MIIS is to supply the mobile node mainly with static information to help in the decision making. Dynamic information about the network parameters can be gathered by the MIH event and command services explained before.

The information elements provided by the MIIS are grouped as follows:

- General Information: These elements provide general static information concerning the network (network type and operator identifier.)

- Access-network-specific-information: These elements provide information concerning network's operator and technology. Like cost, security specifications and QoS parameters.

- Point of attachment information: These elements provide information for each point of attachment as the geospatial location, bandwidth, and Mac address. Information related to the available services in the PoA is provided too.

Chapter 4

Multicriteria decision making

4.1 Introduction

Multiple Attribute Decision Making (MADM) is management decisions aids used in evaluating competing alternatives defined by multiple attributes. MADM problems are diverse, however all of them share the characteristics shown below:

- *Alternatives*: A limited number of alternatives (option, policy, action or candidate) are prioritized, screened, selected and/or ranked. The number of alternatives can be from several to thousands. As example the number of computer brands available in the market which a user can choose to buy a laptop are less than 12. However the number of applicants for an scholarship in a well ranked university are normally more than 1000.

- *Multiple attributes*: Each problem has specific attributes that must be generated by the decision maker to take a decision based in a specific criteria. The number of attributes depends of the nature of the problem. For example the number of attributes (eg. price, fuel consumption, ride comfort, warranty period, safety) which are considered to buy a family car are less than 10. However the number of attributes considered for selecting a site to build a hospital can be more than 1000.

- *Incommensurable Units*: Each attribute considered in the decision criteria has different units of measurement. For example for the family car problem some attributes are tangible, the price is measured in dollars, fuel consumption is measured in miles, the warranty period is measured in years or months. However the safety is considered as an intangible factor and it cannot be measured.

- *Attribute Weights*: The relative importance of each attribute must be assigned by the decision maker or obtained by Attribute Weighting methods.

- *Decision Matrix*: A MADM problem can be expressed in matrix format for decision criteria comparisons.

4.2 Classification of MADM methods

In [11] the authors classify a group of 13 MADM methods according to type of information provided by the decision maker as it is shown in Figure 3.1.

It can be observed when no information is given the Dominance method is applicable. The dominance method stands that one strategy is better than another strategy for one player, no matter how that player's opponents may play. If information is obtained the Maximin or Maximax method is applicable. Where Maximin method is a criteria for minimizing the maximum possible loss. On the other hand Maximax is a criteria for obtaining the maximum possible gain of all other courses of action possible in given circumstances. If information of the attribute is given, a subclassification based in the salient feature information provided by the decision maker can be done. The information provided can be a standard level (eg the minimum acceptable) of each attribute or it might be attribute weights evaluated by ordinal or cardinal scales.

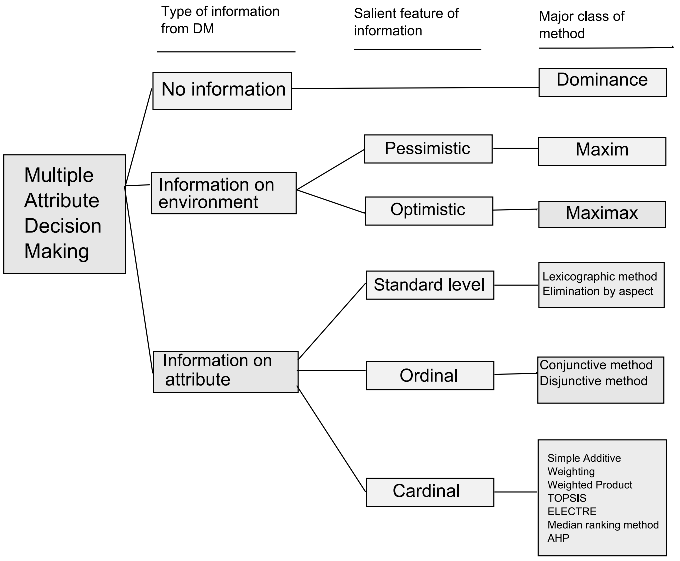

Figure 4.1: Taxonomi of MADM methods

4.3 Attribute Generation, data and weight

The main idea of MADM methods is to obtain an index from multidimensional data to estimate the value of the different alternatives. The analysis begins defining the criteria (attributes) to evaluate relevant goal achievements. Alternatives are assessed over the established criteria. Frequently some attributes (criteria) are more important that others for the decision maker. Furthermore attributes can be described quantitatively of qualitatively. For the example of buying a family car described at the beginning of this chapter the qualitative attributes are price and fuel consumption which can be measured in dollars and kilometers per liter. However security cannot be measured quantitatively. Each attribute has different units of measurement. Due to most of the MADM methods require homogeneous data type, data transformation techniques become necessary.

4.3.1 Attribute generation

Since attributes are the criteria to evaluate the different alternatives into the decision making problem. Attributes must represent the desired mission. The proposed method is to derive the attributes hierarchically from a super goal. The author in [12] proposes that a desirable list of attributes should be based on the following conditions:

- *Be complete and exhaustive*: All the performance attributes which can infer in the final decision should be considered on the list .
- *Contain mutually exclusive items*: The attributes considered on the list must be independent entities among. This will prevent double counting.
- *Be restricted to performance attributes of the highest level of importance*: This list of attributes should be treated as the central core which lower level criteria should be subsequently derived.

The super goal at the top of the hierarchy it is usually quite abstract (eg. the best job, a better quality of life). It becomes less following the hierarchy down until a measurable goal as “personal income” is reached. The lower level attributes should also be coherent, independent and logical as a group.

As it is exposed in [13], the major number of sub attributes are limited to nine. This quantity represents the maximum number of information as an observer can give us about an object on the basis of absolute judgment.

A hierarchy of attributes for evaluating manufacturing plant sites is shown in Figure 4.2. It consists of four levels. As it can be observed four major attributes are identified at the top of the hierarchy which characterize a good site: less cost, higher productivity, better community relation, better living condition. Less cost can be assessed for instance by two sub attributes capital cost and operating cost. When a quantitative attribute cannot be achieved from the beginning it can be divided in sub attributes.

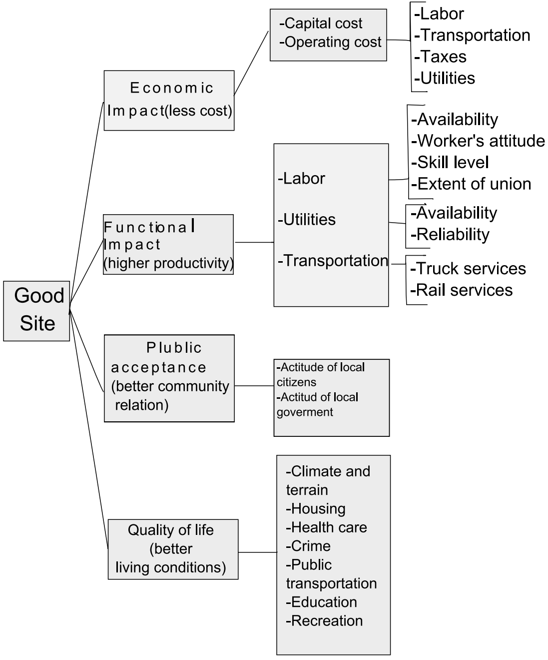

Figure 4.2: A proposed hierarchy for evaluating plant sites

4.3.2 Attribute Weighting

As it was exposed before weights assignment plays an important role into the MADM process. The assignment of weights express the importance of each attribute compared to others for the decision maker. The weights indicate which attribute is more important in a quantitative way. Table 4.1 [11] shows an example of the U.S Department of Commerce which established the Malcolm Baldrige Award in order to stimulate the American companies to improve quality and productivity. As it can be observed the less desirable attribute is the leadership and at the opposite side the most desirable attribute is the costumer focus and satisfaction, which reflects the Departments focus on the costumer.

Table 4.1: The 1992 Malcom Baldrige Award; Examination Items and Point Values

Categories (Attributes)	Point Value	(Weight)
1.0 Leadership	90	(.09)
2.0 Information and analysis	80	(.08)
3.0 Strategic quality planing	60	(.06)
4.0 Human resource development and management	150	(.15)
5.0 Management of process quality	140	(.14)
6.0 Quality and operational results	180	(.18)
7.0 Customer focus and satisfaction	300	(.30)
Total	1000	(1.00)

MADM methods require information regarding the weight of the attributes which should be provided by the decision maker. The decision maker provides this information based in an ordinal or cardinal scale. Usually the decision maker provides the attribute's weight in an ordinal scale. However the MADM methods require the weight information based in a cardinal scale. Cardinal weights are expressed by $w = [w_1,w_2,...,w_j,...,w_n]$ where w_j is the weight assigned to the *jth* attribute. Hence cardinal weights are normalized to 1 as it is expressed in the next condition $\sum w_j = 1$.

4.3.2.1 Weights from ranks

An easy way to assign the corresponding weight to each attribute is to list the attributes in rank order. The most important at the beginning and the less important at last. The cardinal weighting scale can be obtained from one of the following formulas (4.1) and (4.2) [11]. Where r_j is the rank of the *jth* attribute.

$$w_j = \frac{\frac{1}{r_j}}{\sum_{k=1}^{n} \frac{1}{r_k}} \tag{4.1}$$

$$w_j = \frac{n - r_j + 1}{\sum_{k=1}^{n}(n - r_k + 1)} \tag{4.2}$$

The weights obtained by the first formula are called *rank reciprocal weights* and the weights obtained by the second one, *rank sum of weights.* When two or more attributes are tided in the ranking, their mean ranking is used. For example if two attributes have the position fifth and sixth respectively the value that should be used for both of them is 5.5.

Ranking a set of attributes impose several difficulties for the decision maker. Furthermore it can be solved doing pairwise comparisons and storing them in a judgments matrix as it is shown in Table 4.2 [14]. If there are n attributes in the list, a number of $\frac{n(n-1)}{2}$ comparisons should be made. For the example of Table 4.2 a set of 6 comparisons is performed between the different attributes: $(x1, x2)$, $(x1, x3)$, $(x1, x4)$, $(x2, x3)$, $(x2, x4)$, $(x3, x4)$. In this matrix shown in Table 4.2 the symbol “p” is placed in the (i, j) cell when the comparison follows the relationship $xi > xj$ otherwise the symbol “n” is placed in the cell. In the last column this table labeled as $\sum p$ represents the frequency that an attribute is judged higher in the pairwise judgment. The attribute with the higher $\sum p$ is ranked first and with the lower is ranked at the last.

Table 4.2: Pairwise Comparison Judgments

	x_1	x_2	x_3	x_4	$\sum p$
x_1	1	n	n	p	1
x_2	p	1	p	p	3
x_3	p	n	1	p	2
x_4	n	n	n	1	0

4.3.2.2 Ratio Weighting

This method compare the attributes asking for the ratio within them. It means how many times is the attribute x_i more important than the attribute x_j. To obtain consistent and realistic weights from this method a number of $\frac{n(n-1)}{2}$ pairwise comparisons are needed.

Thomas L. Saaty [18] proposes the following steps to obtain the weights of the attributes:

1. The decision makers should perform $\frac{n(n-1)}{2}$ pairwise comparisons within the n attributes in order to fulfill a pairwise comparison matrix. Each element into the matrix is defined as $a_{ij} = \frac{wi}{wj}$ which represents the ratio between the compared attributes. The following properties should be fulfilled for all the elements into the comparison matrix $a_{ij} = \frac{1}{a_{ji}}$ and $a_{ii} = 1$.

2. To compute the weights of the attributes the geometric mean method should be applied over each row. Therefore a normalization of the scores is performed as it is show in Table 4.3 and 4.4.

Table 4.3: Pairwise Comparison Matrix

	X1	X2	X3				
X1	$\frac{w1}{w1}$	$\frac{w1}{w2}$	$\frac{w1}{w3}$	$=$	1	2	4
X2	$\frac{w2}{w1}$	$\frac{w2}{w2}$	$\frac{w2}{w3}$	$=$	$\frac{1}{2}$	1	3
X3	$\frac{w3}{w1}$	$\frac{w3}{w2}$	$\frac{w3}{w3}$	$=$	$\frac{1}{4}$	$\frac{1}{3}$	1

Table 4.4: Geometric Mean Method

	Geometric	Mean	Method		
X1 $=$	$(1 \times 2 \times 4)^{\frac{1}{3}}$	$=$	1.99	$=$	0.55
X2 $=$	$(\frac{1}{2} \times 1 \times 3)$	$=$	1.14	$=$	0.32
X3 $=$	$(\frac{1}{4} \times \frac{1}{3} \times 1)$	$=$	0.43	$=$	0.12
	sum	$=$	3.56	$=$	1.00

4.3.3 Quantification of Qualitative Rating

The MADM methods can by described by tangible or intangible attributes. Tangible defines attributes than can be measured like price (dlls), distance (meters), fuel consumption (kilometers per liter). However intangible or qualitative attributes cannot be measured in the same way. Therefore it is necessary to assign numerical values to intangible attributes in order to incorporate them into the MADM methods. Hence a method which assigns numerical values to intangible data by scaling is the preferred approach proposed in [11].

The authors describe the Likert-type scale which defines a set of statements to cover the intangible attributes. After the statements are defined a quantitative value is assigned to each of them. For example for the development of a new flavored beverage a scale of five points is defined due to the flavor of the beverage. The statements are (very good, good, medium, low, very low.) To score the scale the statements are associated with 1, 2, 3, 4, 5 reading from very low to very good. Other scale of seven or nine points can be used although it depends of the problem's context.

The Likert-type scale is an interval scale. Therefore the intervals between the statements are meaningful however the ratios between the scale scores has no meaning. Hence a scale system as 1, 3, 5, 7, 9 can be used . Note that the difference for low and very low is the same as the difference between good and very good. The ratios in both scales differ however they have no meaning.

The statements used in the example above cannot be suitable to describe other qualitative attributes. For example if we are comparing size the size the statements can be: large, large, medium, small, very small. If the price is the attribute which should be described the possible statements are (very expensive, expensive, fair price, cheap, very cheap). For other kind of attributes a set of statements to describe them should be found in order to perform the quantification of the attribute.

4.3.4 Normalization of attribute ratings

When MADM methods are applied, the different units used for comparing attributes may cause computational problems. Furthermore optimal normalization techniques are useful to perform inter attribute and intra attribute comparisons. After the normalization is done the attribute ratings have dimensionless units. Therefore as large becomes the attribute's rating, the attribute will be more preferable for the decision maker.

Attributes can be classified in three groups [11] before normalization is applied:

1. Benefit attributes: Offer increasing monotonic utility. The greater the attribute value the more its preference. For example the income received by an employee.
2. Cost attributes: Offer decreasing monotonic utility. The greater the attribute value the less its preference. An example can be the price of an specific product.
3. Non monotonic attributes: Offer non monotonic utility. Such as the average temperature in a building or the blood pressure in the human body. For both examples the more suitable values are located in the middle of the scale.

Normalization method for attributes:

- Linear normalization for benefits: This procedure divides the rating of a certain attribute by its maximum value (4.3) [11].

$$r_{ij} = \frac{x_{ij}}{x_j^*}; i = 1, ..., m; j = 1, ..., n \tag{4.3}$$

Where x_j^* is the maximum value of the jth attribute and r_{ij} is the normalized attribute.

- Linear normalization for costs: Cost attributes can be transformed in benefits by taking the inverse rating. Then the transformed benefit attribute follows the same normalization process. In this case the normalized attribute is (4.4) :

$$r_{ij} = \frac{x_j^{\cdot}}{x_{ij}} \tag{4.4}$$

Where $x_j^{\cdot}$ is the minimum value of the jth attribute.

4.4 The Analytical Hierarchy Process

4.4.1 Introduction

The interaction of basic observations on human nature, analytical thinking and measurements have influenced the development of the Analytical Hierarchy Process (AHP) [18]. The Analytical Hierarchy Process is a useful model which allows individuals or groups to define problems by making their own assumptions and deriving a solution based on them. The AHP provides an advantageous tool to solve problems quantitatively.

The AHP provides a framework to structure the problem in a hierarchy based in logic, intuitions and experience in order to incorporate judgments and personal values in a logical way. Once the model is accepted the AHP allows the user to understand, identify and assess the interactions of one part of the problem with those on another to conceive the system as a whole. It enables the user to consider the complete problem to study the simultaneous interactions of its components within the hierarchy.

The AHP is a tool which permits a revision of the elements in the problem hierarchy in order to change their judgments. It allows the user to test the consistence of the outcome to changes in information. The AHP is a process which should be iterated over time for a progressive refinement of the hypothesis in order to get a complete understanding of the system.

The AHP provides a framework for group participation in the decision making since the relative importance of judgments depends of the point of view of each decision maker.

The AHP method can be applied to real problems without the intervention of an expert in the field. It can be very useful for allocating resources, planning, analyzing the impact of a policy and resolving conflicts.

The major advantages of AHP can be resumed in the sentences below:

1. A practical way to deal quantitatively with different kinds of functional relations in a complex world.

2. It is a tool for integrating forward and backward planning in an interactive manner that reflect the judgments of all relevant managerial personnel.

3. It provides:

- A new way to integrate hard data due to intangible and tangible factors.

- A framework which provides support during the group decision making process.

To have a better understanding of the AHP, three basic principles should be identified: the principle of constructing hierarchies, the principle of establishing priorities and the principle of logical consistency.

- Structuring Hierarchies: Our mind has the ability to perceive and identify things and ideas to communicate what it is observed. For a complete understanding our mind structure complex reality and divide it into constituent parts and so on hierarchically. The number of parts can vary between five and nine [11].
- Setting Priorities: Our mind has the ability to establish a trade off among the things that it observe. To compare and discriminate pairs of similar things following a predefined criteria. Therefore the outcome of this procedure is to establish a scale of preference among the different compared alternatives [18].
- Logical Consistency: Our mind has the ability to establish trade offs between the alternatives in such a way that they are coherent. It means that they relate to each other and the relations exhibit certain consistency. Consistency means that similar ideas or objects are grouped according to homogeneity and relevance. Also means that intensities of relations among ideas or objects based on a particular criterion justify each other in some logical way [18].

4.4.2 Analyzing and structuring hierarchies

Complex systems can be understood better by breaking them down into small parts, to structure the elements hierarchically and then to set the relative importance of the elements at each level of the hierarchy. Hierarchies are a fundamental tool of the human mind. They allow the user to identify the elements of a problem grouping the elements into homogeneous sets and classify the set in different levels. Furthermore the hierarchies should be a flexible enough tool to help the human mind to understand the complexity of reality.

4.4.2.1 Classifying hierarchies

Hierarchies can be divided in two types: structural and functional. In structural hierarchies the system is decomposed in descending order according the structural properties as shape, color, size, texture. Structural hierarchies are the best example of how the human mind analyzes the reality breaking down the perceived objects into clusters and so on into smaller clusters.

On the other hand functional hierarchies decompose the system into small parts according to the relationships within them. The hierarchy is structured in the way that each group of elements in the hierarchy occupies only one level.

The top level is called the focus which contains the main goal of the process. For the subsequent elements the number is limited to nine elements. As a general rule the elements in one level should be of the same order of magnitude since a set of comparisons must be performed between the elements in one level based in a pre-defined criteria in the next higher level. However if the discrepancy between the elements is considerable, they should be located in different levels.

All the hierarchies are functional although some are complete which means that the elements in one level share all the properties in the higher level. The rest are incomplete, where the elements share just some of the properties in the next higher level.

4.4.2.2 Constructing hierarchies

Experience suggests that the AHP can be applied to a wide area of contexts giving successful results. The only limitation is ourselves' experience and the way to decompose and synthesize the problem. The best form to structure the hierarchy is to adapt it based on the kind of decision to be made. We could start defining the goal of the problem at the top of the hierarchy. In the next level we should specify the decision criteria parameters which will be involved during the decision making process. The last level of the hierarchy consists on a set of several alternatives.

For example, consider the problem defined on Figure 4.3: an undergraduate student has five options to continue with his education. These options are listed at the bottom of the hierarchy. The criteria parameters which the alternatives will be evaluated are located in the next level; these options are: prestige, quality of the research, reputation of the professors, educational cost and live expenses. The alternatives in this problem will be judged based on the their contribution to the overall goal of the problem.

Furthermore the hierarchy should be designed with a range of flexibility. Hence new criteria can be added or considered during the development of the model. However after we have made the set of comparisons and obtain the overall priorities. Perhaps we might still have some, doubts in the final decision in this case we can go through the process and change some judgments or criteria parameters.

4.4.3 Establishing priorities

The last step of the AHP is to establish a scale of priorities between the elements in the hierarchy in order to synthesize our judgments for obtaining a set of overall priorities, checking the consistency of these judgments and coming to a congruent final decision based in the output of the process.

The AHP allows the user to solve complex problems by structuring ideas hierarchically and then perform the paired comparisons of the elements in

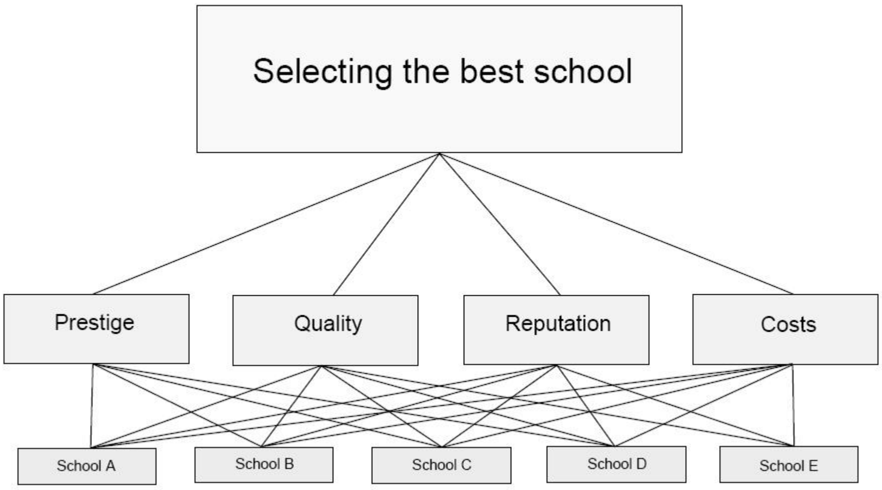

Figure 4.3: Hierarchy for selecting a school

the hierarchy through synthesis. These paired comparisons are based on logical thinking and in our own experience.

4.4.3.1 Making judgments

The first step in establishing priorities into the AHP process is to perform pairwise comparisons among the different alternatives following a specific criteria. For the pairwise comparisons, a matrix is the well-liked form. The matrix is a powerful tool which offers the possibility of testing consistency, obtaining information based in all the possible comparisons among the elements and analyzing the sensitivity of the overall priorities for a possible change in judgments.

The pairwise comparison process starts at the top of the hierarchy selecting the criteria P to perform the comparisons of the elements taken from the level below. The alternatives compared in this example are E1, E2, E3 and so on until E5. The matrix which contains this comparison is illustrated in the Figure 4.4.

As it can be observed, a set of comparisons between the first element in the column of the left is performed among the elements in the row on top with respect to criteria P. The same process will be repeated for each element of the left column. In order to make the comparisons the user should ask himself how much this element contributes, influences or fulfills the criteria which is compared. To fill the matrix, a comparison scale has been defined by T. Saaty [18] to represent the relative importance between the alternatives compared under a predefined criteria as it is shown in Figure 4.5. This scale provides a set of values from 1 through 9 which are useful to compare a pair

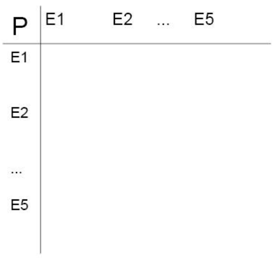

Figure 4.4: Sample matrix

of elements in one level of the hierarchy respect to the criteria defined in the next higher level.

Figure 4.5: The Fundamental Scale for Pairwise Comparisons

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	For compromise between the above values

When an element in the matrix is compared with itself, the comparison must give as result the unit. Hence the elements in the main diagonal of the matrix should be equal to 1. After the comparison of the first element of the left hand column matrix with the second element of the row on top is done. The reciprocal value of this comparison can be used for the comparison of the second element of the left hand column with the first element of the row on top. As it can be observed there is a trade off between the elements in the comparison matrix. Furthermore it is not possible to use simply and arbitrary numbers for ranking the elements according to the criteria. The numbers assigned for comparison should be selected with care to express the strength with each element contribute to satisfy the proposed criteria. To ensure that at the end consistent results can be obtained.

4.4.3.2 Deriving priorities

To synthesize the judgments in the pairwise comparison matrix we have to weigh and add to obtain a single number in order to get the priority of each element. As it is shown in Table 4.5, we need to decide which of the three new cars: a Renault Megane, a Volvo S40 and a Peugeot 206 buy on the basis of comfort.

Table 4.5: Deriving priorities by an AHP matrix.

Comfort	Peugeot	Megane	Volvo
Peugeot	1	$\frac{1}{3}$	$\frac{1}{6}$
Megane	3	1	$\frac{1}{2}$
Volvo	6	2	1

For this propose we build a matrix based on criteria of comfort which is listed in the upper left-hand corner, the cars are listed on the left hand column and in a row on top. The main diagonal of the matrix is fulfilled with ones. Therefore the three judgments above the diagonal are the reciprocals to the judgments below. Hence in order to establish a relationship between the different alternatives. We ask ourselves how much comfortable is an average Peugeot 206 than an average Megane and an average Volvo S60. Based on our own thinking we decide that a Megane is 3 times more comfortable than a Peugeot and than a Volvo is 6 times more comfortable than a Peugeot. Furthermore a Volvo S60 is 2 times more comfortable than a Megane. After we have defined the relationships for the elements below the diagonal. The value of the elements above the diagonal can be obtained by taking the inverse of these values.

As a general rule, each element listed in the left-hand column is compared with the elements on the top row. If the comparison is favorable the cells is fulfilled with an integer in the opposite case the judgment is a fraction. Furthermore, the reciprocal value is entered in the position where the second element appears in the left hand column and the first element appears in the row on top.

4.4.3.3 Calculating the priorities

Using an approximation method: In order to get the priorities of each of the three proposed alternatives shown in the first matrix below, we have to synthesize the judgments and get an approximate of the priorities of these cars based in comfort. To do so we have to add the values over each column as it is shown in Table 4.6. Furthermore the column should be normalized dividing each entry in the column by the total sum of it as it is shown in Table 4.7. The output of this process are the overall priorities or preferences for the three alternatives as it is show in Table 4.8. The priorities in this case for the Peugeot 206, the Renault Megane and the Volvo S60 are: 0.1, 0.3 and 0.6 respectively.

Table 4.6: Normalization procedure for an AHP matrix (approximation method).

Comfort	Peugeot	Megane	Volvo
Peugeot	1	$\frac{1}{3}$	$\frac{1}{6}$
Megane	3	1	$\frac{1}{2}$
Volvo	6	2	1
Total	10	$\frac{10}{3}$	$\frac{5}{3}$

Table 4.7: Normalization procedure for an AHP matrix (approximation method).

Comfort	Peugeot	Megane	Volvo
Peugeot	$\frac{1}{10}$	$\frac{1}{10}$	$\frac{1}{10}$
Megane	$\frac{3}{10}$	$\frac{3}{10}$	$\frac{3}{10}$
Volvo	$\frac{3}{5}$	$\frac{3}{5}$	$\frac{3}{5}$

Table 4.8: Deriving priorities (approximation method).

Deriving Priorities			
Peugeot	$\frac{\frac{1+1+1}{10}}{3}$	$=\frac{1}{10}$	=0.1
Megane	$\frac{\frac{3+3+3}{10}}{3}$	$=\frac{3}{10}$	=0.3
Volvo	$\frac{\frac{3+3+3}{5}}{3}$	$=\frac{3}{5}$	=0.6

Using the exact method: As it can be observed in Table 4.9 the value of the first row second column represents the value of A over B on top. This value is equal to the value of the first row and fourth column comparing A with D multiplied by the value of the fourth row and the second column comparing D with B. In another way the dominance of A over B can be obtained too by the dominance of A over D multiplied by the dominance of D over B. This process is a two step dominance. To check all such dominances in two steps the matrix of judgments should be multiplied by itself which gives us all the products necessary by passing through intermediate activities and adding these products. Furthermore this is not the only way of how A dominates B a three step dominance can be considered too. The dominance between A and B can be expressed by the dominance of A over C, then C over D and finally D over B. All the three steps dominance are captured by multiplying the matrix by itself three times. However to ensure that all possible dominances are covered we have to consider all the powers of the matrix. When the matrix is consistent any power of the matrix is equal to a constant multiplied by the initial matrix due to the matrix by itself contains all the information needed. However when the matrix is inconsistent the priorities should be obtained as follows: First each time the matrix is raised to powers one by one. Therefore we use the approximation method to compute the priorities for each power of the matrix. Furthermore there will be a big number of priorities for the same alternative. Hence an average of the priorities is taken to obtain a unique priority for each alternative. The resultant is known as the eigenvector of the original matrix. In practice this procedure is done by raising the matrix to a sufficiently high power.

Table 4.9: Deriving priorities (exact method).

	A	B	C	D
A	1	2	2	4
B	$\frac{1}{2}$	1	1	2
C	$\frac{1}{2}$	1	1	2
D	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	1

4.4.4 Consistency

In a decision making problem it is critical to know if our judgments are consistent within them. Because a low consistency will make that our decisions seem to be random. However perfect consistency is difficult to obtain. As it is shown in Table 4.6 to Table 4.8 the judgments were consistent. In real life it is almost impossible to obtain perfect consistency since specific circumstances often influence preferences, changing the relationships between the elements.

For example if we prefer basketball to football and then we prefer football over baseball. In perfect consistency we must prefer basketball over baseball. However the same person sometimes may prefer baseball over basketball depending of circumstances. This is a normal fact in real life which leads to inconsistency. Furthermore when we integrate new experiences to our personal background, previous relationships will change, this action will generate inconsistency in our judgments. Although there is no necessity of perfect consistency if there is enough coherence among the objects of our experience. Hence there should be a trade off between tolerable inconsistency of the judgments and coherence among experience.

The AHP measures the grade of consistency into matrix's judgments based in the consistency ratio. The average value for the consistency ratio for a matrix of judgments is normally less than 10%. Otherwise the judgments in the matrix give the impression of randomness and should be revised.

Table 4.10: Normalization procedure for an AHP matrix

Comfort	Peugeot	Megane	Volvo
Peugeot	1	$\frac{1}{3}$	$\frac{1}{6}$
Megane	3	1	$\frac{1}{4}$
Volvo	6	4	1
Total	10	$\frac{16}{3}$	$\frac{17}{12}$

Table 4.11: Normalization procedure for an AHP matrix

Comfort	Peugeot	Megane	Volvo
Peugeot	$\frac{1}{10}$	$\frac{1}{16}$	$\frac{2}{17}$
Megane	$\frac{3}{10}$	$\frac{3}{16}$	$\frac{3}{17}$
Volvo	$\frac{6}{10}$	$\frac{3}{4}$	$\frac{12}{17}$

Table 4.12: Deriving priorities

Deriving Priorities			
Peugeot	$\frac{\frac{1}{10}+\frac{1}{16}+\frac{2}{17}}{3}$	$=\frac{127}{1360}$	=0.09
Megane	$\frac{\frac{3}{10}+\frac{3}{16}+\frac{3}{17}}{3}$	$=\frac{301}{1360}$	=0.22
Volvo	$\frac{\frac{6}{10}+\frac{3}{4}+\frac{12}{17}}{3}$	$=\frac{233}{340}$	=0.68

As an example consider the comparison based in comfort between: a Peugeot, a Megane and a Volvo which is shown in Table 4.10 to Table 4.12. If the judgment in the second row third column is change from$\frac{1}{2}$ to $\frac{1}{4}$ as it is done in Table 4.10. Furthermore its reciprocal is entered in the third row second column. Therefore as we can observe the percentages of the overall priorities present a variation compared with the previous example. When we have perfect consistency. The overall priority values represent the priority vector of the cars based in comfort. Hence the value of the priority vector is an approximation. When the judgments are perfectly consistent the values from the approximate method and the exact method are identical; and when nearly consistent the values are close [18].

As it is observed where inconsistency is presented in the judgments the priority values are changed. Hence in order to measure the level of inconsistency presented in the pairwise comparison matrix. This matrix should be compared with a matrix where the judgments are generated randomly. To perform this operation the first column of the inconsistent matrix is multiplied by the priority value of 0.09, then multiply the second column by 0.22 and so on. Table 4.13 shows the values obtained by this operation.

Table 4.13: Measuring the level of inconsistency in an AHP matrix

Comfort	Peugeot (0.09)	Megane (0.22)	Volvo (0.68)	Row-Total
Peugeot	$\frac{9}{100}$	$\frac{11}{150}$	$\frac{17}{150}$	$\frac{83}{300}$
Megane	$\frac{27}{100}$	$\frac{11}{50}$	$\frac{17}{100}$	$\frac{33}{50}$
Volvo	$\frac{27}{50}$	$\frac{22}{25}$	$\frac{17}{25}$	$\frac{21}{10}$

Furthermore the entries of each row should be added to obtain the total over each row. Now this column should be divided by the corresponding entry of the priority vector. After the division is performed we can obtain the average of the three entries $\frac{\frac{83}{27}+3+\frac{105}{34}}{3} = 3.054$

The result of this operation is know as λ_{max}. The index which measures the grade of inconsistency (CI) is obtained in the following way for a matrix of three elements (where n is the number of elements in the matrix) : $\frac{\lambda_{max}-n}{n-1}=\frac{3.054-3}{2}=0.027$. As it can be observed from Table 4.5 the random value of the CI is 0.52. Therefore the consistency ratio (CR) is $\frac{0.027}{0.52} = 0.05$ which is less than the 10% which means that the grade of inconsistency is acceptable for this matrix.

Table 4.14: Average consistencies

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

4.4.5 Hierarchical SAW method

The main goal of the AHP is to enable a decision maker to structure a MADM problem in a form of an attribute hierarchy. A hierarchy must have at least three levels: The focus of the problem at the top, the criteria to evaluate the alternatives and the competing alternatives at the bottom. To exemplify this issue a problem of a female accountant who needs to decide between three alternatives: (A1) partner in a large corporation, (A2) her own consulting firm and (A3) a faculty position at a university is shown in this section.

Figure 4.6 shows the hierarchy used in this problem by the female accountant [11]. As it can be observed level 1 it is focused on global job satisfaction. Level 2 comprises the decision criteria parameters to solve the problem: Money (M), Job Security (S), Growth (G) and Work Environment (W). Level 3 contains the three job alternatives A1, A2 and A3.

Each decision criteria parameter shown in Figure 4.6 contribute in a different way to her job satisfaction. In order to decide on the relative importance within the four criteria parameters she performs pairwise comparisons

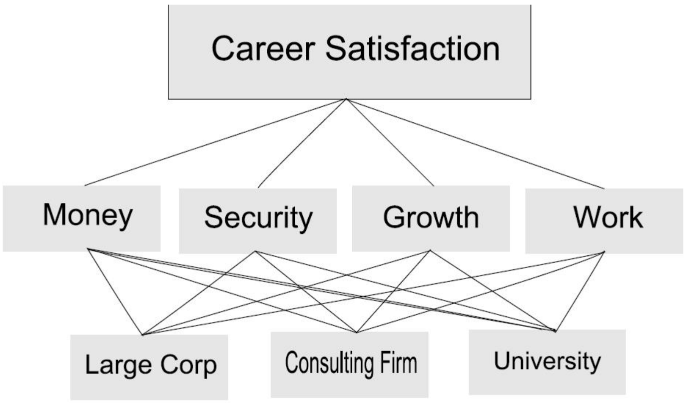

Figure 4.6: AHP hierarchy of the problem

which are easier to do than a comparison of four criteria simultaneously. To help the decision maker to perform pairwise comparisons Saaty [18] created a nine point intensity scale of importance between two elements A and B as it is shown in Figure 4.5. Intermediate values (2, 4, 6, 8) can be used to express a compromise between the preferences.

In the accountant female problem there are four criteria parameters in level two. Therefore a number of six pairwise comparisons which are shown in Table 4.15 to Table 4.20 should be performed among the decision criteria respect to level one on the hierarchy. This comparisons can be concisely contained in a matrix whose element at row i and column j in the ratio of row i and column j. That is,

Table 4.15: AHP pairwise comparison matrix

	M	S	G	W
M	1	$\frac{M}{S}$	$\frac{M}{G}$	$\frac{M}{W}$
S	$\frac{S}{M}$	1	$\frac{S}{G}$	$\frac{S}{W}$
G	$\frac{G}{M}$	$\frac{G}{S}$	1	$\frac{G}{W}$
W	$\frac{W}{M}$	$\frac{W}{S}$	$\frac{W}{G}$	1

Table 4.16: AHP comparison matrix for the decision criteria parameters

	M	S	G	W
M	1	7	1	7
S	$\frac{1}{7}$	1	$\frac{1}{3}$	2
G	1	3	1	5
W	$\frac{1}{7}$	$\frac{1}{2}$	$\frac{1}{5}$	1

Then the comparisons of the elements of level 3 with respect to the decision criteria of level 2 should be performed in the following way.

Table 4.17: Pairwise comparisons for the criteria of Money

for M	A_1	A_2	A_3
A_1	1	$\frac{1}{3}$	2
A_2	3	1	5
A_3	$\frac{1}{2}$	$\frac{1}{5}$	1

Table 4.18: Pairwise comparisons for the criteria of Security

for S	A_1	A_2	A_3
A_1	1	3	$\frac{1}{5}$
A_2	$\frac{1}{3}$	1	$\frac{1}{7}$
A_3	5	7	1

Table 4.19: Pairwise comparisons for the criteria of Growth

for G	A_1	A_2	A_3
A_1	1	$\frac{1}{5}$	2
A_2	5	1	7
A_3	$\frac{1}{2}$	$\frac{1}{7}$	1

Table 4.20: Pairwise comparisons for the criteria of Work

for W	A_1	A_2	A_3
A_1	1	$\frac{1}{3}$	$\frac{1}{5}$
A_2	3	1	$\frac{1}{3}$
A_3	5	3	1

After the decision matrix has been fulfilled, the next step is to obtain the weights of each element into the matrix. Therefore for this example the geometric mean of a row suggested by Saaty [18] provides accurate results in most situations. This method can be performed following the next steps.

- Multiply the n elements in each row
- Take the *nth* root
- Put the results in a new column
- Normalize the new column

The weight for the decision criteria parameters are computed as it is shown in Table 4.21 :

Table 4.21: Computing the weights of the criteria parameters

	Geometric	Mean	Method
M	$(1 \times 7 \times 1 \times 7)^{\frac{1}{4}}$	$= 2.65$	$= 0.48$
S	$(\frac{1}{7} \times 1 \times \frac{1}{3} \times 2)^{\frac{1}{4}}$	$= 0.56$	$= 0.10$
G	$(1 \times 3 \times 1 \times 5)^{\frac{1}{4}}$	$= 1.97$	$= 0.36$
W	$(1 \times 3 \times 1 \times 5)^{\frac{1}{4}}$	$= 0.35$	$= 0.06$
sum		=5.53	=1.00

In the same way the weights of each decision matrix shown above are obtained. Hence at the end a matrix which contains the weights of the alternatives based on each decision criteria parameter is computed and shown in Table 4.22.

Table 4.22: Computing the weight of the alternatives based on each decision criteria parameter

	M	S	G	W
A_1	0.23	0.19	0.17	0.10
A_2	0.65	0.08	0.74	0.26
A_3	0.12	0.73	0.09	0.64

The last part is to compute the contribution of each of the alternatives to the accountant's career satisfaction. The overall priority for each alternative is obtained by multiplying the weight of each criteria parameter by the contribution of the alternative. The contribution of the overall priority for the alternative A2 is performed as follows: $0.48 \times 0.65 + 0.10 \times 0.08 + 0.36 \times 0.74 + 0.06 \times 0.26$=0.602.

In the same way the calculations for the other alternatives were performed for A1 0.l966 for A3 0.2014. Hence the logical option is A2.

Chapter 5

A Probabilistic Extension of the AHP method for Network Selection

Handover decision deals with the problem of decision making about a specific criteria within a certain number of candidate networks from different technologies and service providers. Furthermore the handoff decision process can be conceived as a MADM problem [14]. Since the implementation of the handover decision engine is out of the scope of IEEE 802.21, an effort to provide a trustable solution regarding the handoff decision scheme should be done. Furthermore, we present in this work a novel approach which considers the uncertainty during the decision process to provide the mobile with more parameters to make the selection of the target network with a higher level of confidence. Traditionally, handoff decision making has been studied as a deterministic MADM problem [6, 13]. For this purpose the AHP (Analytic Hierarchy Process) [7] is a well known decision making support which takes into account all different aspects (quantitative and subjective or non-quantitative) involved in the decision making process [8, 9]. However the major drawback of the AHP is that it does not consider the uncertainty related to the judgments into the pairwise comparison matrix [9, 18]. It is assumed than when the relative weights are entered into the matrix they should be represented by deterministic quantities. Although in the real world decision makers are always subject to uncertainty when they express their judgments since the human mind is not always confident when quantitative evaluations are translated to specific quantities. Besides not only non quantitative aspects are subject to uncertainty, absolute measurements (e.g. bandwidth, delay, jitter) have inherent uncertainties due to statistical errors [9]. Therefore it is quite normal to have uncertainties in the relative weights of the comparison matrix. Furthermore if there are uncertainties present into the ratio of the matrix, there must be uncertainties in the derived priority weights of the elements of the matrix as well. This limitation reduces the applicability of the AHP. However in the literature we found some proposals that incorporate the uncertainty of the judgments in the AHP [9, 18]. In this work the handoff decision making problem is conceived as a probabilistic issue in order to consider a mobile node carrying multiple communication sessions. A tradeoff between the different QoS requirements is established for each service class to model this issue as a group decision making problem. Therefore this new proposal incorporates two kinds of uncertainties related to the tradeoff between the QoS requirements for each traffic class and the inherent uncertainties of the absolute measurements related to the conditions of the target network.

5.1 Network Selection Process

We conceive the network selection problem as MADM problem with certain constraints. For this proposal we consider traffic classes with different QoS requirements. It is considered a mobile node which carries two communication sessions simultaneously (voice and video), and needs to execute handover to one of the two candidate networks which provide the best QoS. The AHP hierarchy is shown in Figure 5.1, which is explained below.

- Goal: The aim of the process is to handover the the network which offers the best quality of service for the mobile node applications.
- Alternatives: They are shown at the bottom of the hierarchy. Alternatives are the possible options which a decision maker can choose. In this example the decision must be performed between two networks.
- Criteria: They are the quantitative or qualitative parameters by which the alternatives are judged. As it can be observed in Figure 5.1 we consider: Price, Bandwidth, Delay, Jitter, PER.

5.2 Ranking of Target Networks

In the development of this work. It is assumed in the model that the IEEE 802.21 standard is placed into the network. Therefore the mobile node can obtain the current network conditions of the neighboring networks by the MIS.

For this proposal we consider traffic classes with different QoS requirements. It is considered a mobile node which carries two communication sessions simultaneously (voice and video), and needs to execute handover to one of the two candidate networks which provides the best QoS.

The AHP matrices for voice and video respect to different criteria are shown in Table 5.1. As it is observed, the QoS requirements for each traffic

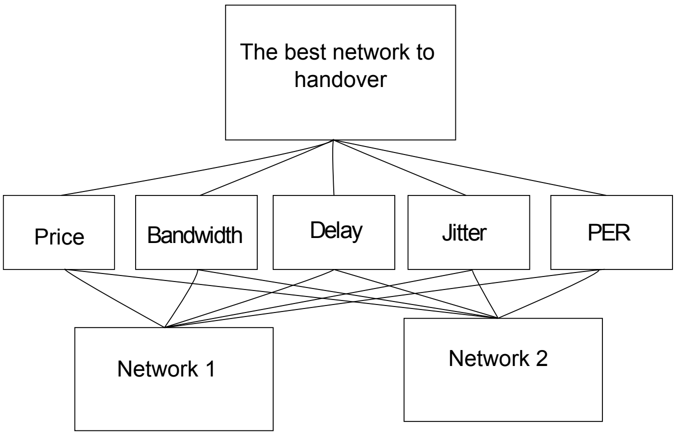

Figure 5.1: AHP hierarchy of the problem

class differ significantly for some of the weights into the matrix. Hence it is not possible to model this problem as a deterministic issue because both application requirements for voice and video should be considered simultaneously in order to handover to the network providing the best QoS for the mobile node. Furthermore it cannot be assumed that while entering the values into the AHP matrix for both communication sessions, the weights can be expressed by single numbers. To provide a complete solution, this issue should be treated as a group decision making problem [3]. Therefore, to represent uncertainty into the pairwise comparison judgments, each position in the matrix should be modeled as a stochastic variable. We take as reference for our work the solution described in [4], where the authors propose a second kind Beta distribution $Be_2(i,j)$ to represent the comparison judgments to consider uncertainty into the decision process. This random variable should have a high probability of being inside the interval defined by the different QoS requirements for each interval of judgments, which are shown in Table 5.2. Following this criteria, the variable a_{ij} of the judgments inside the interval $[L_{ij}U_{ij}]$ into the AHP matrix should fulfill the following conditions:

$$P(a_{ij} < L_{ij}) < \frac{c}{2}; P(a_{ij} > U_{ij}) > 1 - \frac{c}{2} \tag{5.1}$$

Table 5.1: AHP Matrices for each traffic class

Voice	Price	Bandwidth	Delay	PER	Jitter
Price	1	7	1	7	1
Bandwidth	$\frac{1}{7}$	1	$\frac{1}{7}$	1	$\frac{1}{7}$
Delay	1	7	1	7	1
PER	$\frac{1}{7}$	1	$\frac{1}{7}$	1	$\frac{1}{7}$
Jitter	1	7	1	7	1
Video	Price	Bandwidth	Delay	PER	Jitter
Price	1	1	3	7	1
Bandwidth	1	1	3	7	1
Delay	$\frac{1}{3}$	$\frac{1}{3}$	1	3	$\frac{1}{3}$
PER	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{3}$	1	$\frac{1}{7}$
Jitter	1	1	3	7	1

As it is proposed in [4] a deterministic solution must be obtained first. Hence we compute a reciprocal matrix of the values shown in Table 5.2. For each a_{ij} element an average value $a_{ij} = \sqrt{L_{ij} * U_{ij}}$ is calculated to form the reciprocal matrix of the $*a_{ij}$ values; these are shown in Table 5.3.

Table 5.2: AHP Matrix for voice and video

Voice/Video	Price	Bandwidth	Delay	PER	Jitter
Price	1	$[1-7]$	$[1-3]$	7	1
Bandwidth	$[\frac{1}{7}-1]$	1	$[\frac{1}{7}-3]$	$[1-7]$	$[\frac{1}{7}-7]$
Delay	$[\frac{1}{3}-1]$	$[\frac{1}{3}-7]$	1	$[3-7]$	$[\frac{1}{3}-1]$
PER	$\frac{1}{7}$	$[\frac{1}{7}-1]$	$[\frac{1}{7}-\frac{1}{3}]$	1	$\frac{1}{7}$
Jitter	1	$[1-7]$	$[1-3]$	7	1

Table 5.3: AHP reciprocal matrix for the $*a_{ij}$ values

Voice/Video	Price	Bandwidth	Delay	PER	Jitter
Price	1.00	2.64	1.17	7.0	1.0
Bandwidth	0.37	1.0	0.65	2.64	0.37
Delay	0.57	1.52	1.0	4.0	0.57
PER	0.14	0.37	0.24	1.0	0.14
Jitter	1.0	2.64	1.73	7.0	1

Table 5.4: AHP priorities of decision criteria

Price	Bandwidth	Delay	PER	Jitter
0.32	0.12	0.18	0.04	0.32

The matrix presented in Table 5.3 only contains single numbers that can be treated using the traditional AHP method [18]; in order to obtain the weights of the QoS parameters, the pairwise comparison matrix in Table 5.3 is solved using the geometric mean method over each column, which results are shown in Table 5.4. As it can be observed the most important decision parameters are Price and Bandwidth and the less important is PER. Therefore to provide a complete solution, we have to consider the uncertainty due to the absolute measurements of the different parameters (bandwidth, delay, jitter and PER) for each of the candidate networks. Concerning the price, an uncertainty term can be considered too. However this is traditionally modeled as a single value without a standard deviation, as it is considered in this work.

The values of the measurements and the uncertainties due to statistical errors are shown in Table 5.5. As it can be observed, the values containing uncertainty can be described by $w_i = w_i \pm \triangle w_i$. Therefore any quantity derived as the $a_{ij}^{\prime}s$ from the $wi's$ values must have an uncertainty term $\triangle A_{ij}$[25]. Where $a_{ij}{=}a_{ij} \pm \triangle A_{ij}{\rightarrow}\ \frac{w_i}{w_j} \pm \frac{w_i \triangle w_j + w_j \triangle w_i}{w_j^2}$

Although all the diagonal elements in the pairwise comparison matrix must have the uncertainty term $\triangle A_{ii} = 0$, due to the self-comparisons of the decision elements should not contain an uncertainty term [25].

Related to some of the network measurements shown in Table 5.5, some of them are considered as costs (delay, jitter, PER and price) and the rest are considered as benefits. They must be normalized before be inserted into the comparison matrix; for this case the normalization procedure proposed in [11] is applied.

Concerning the benefits, the normalized value of w is $n_{ij} = \frac{w_{ij}}{w*_j}$, where w_j is the maximum value of the $j - th$ attribute. Furthermore, the normalized value for the costs is $n_{ij} = \frac{x_j^{\prime}}{xij}$, where $x_j^{\prime}$ is the minimum value of the jth attribute.

Once the values of the measurements for each target network have been normalized and the uncertainty term related to this normalization has been considered, they can be used to form the pairwise comparison matrices for the target networks respect to the decision criteria. Furthermore, the a_{ij} elements of these matrices will be contained within an interval of judgments. Hence the procedure that we use to perform the calculations shown in Table 5.3 can be performed. The analytical results are obtained by a symbolic computing tool following the classical AHP method, which are shown in Table 5.6. As we observe, this part of the method provides the mobile just with a deterministic solution.

Table 5.5: Measured values for each target network

	Network 1	Network 2
Price	10	20
Bandwidth	1 ± 0.12	2 ± 0.15
Delay	50 ± 4	80 ± 7
PER	0.01 ± 0.001	0.008 ± 0.0001
Jitter	10 ± 1	10 ± 1

Table 5.6: AHP global probabilities

Weight	Network 1	Network 2
Goal	0.55	0.45
Price	0.66	0.33
Bandwidth	0.33	0.66
Delay	0.61	0.38
PER	0.44	0.55
Jitter	0.5	0.5

5.3 Probability of the Ranking to Remain Stable

Furthermore, sometimes when the results are close to each other, as it is shown in our case, it cannot be justified a real confidence on the final decision. Hence to provide the mobile with more decision parameters, the probabilistic extension of the AHP method proposed in [4] can be applied to obtain a second decision index. In this case, when the handoff decision is conceived as a probabilistic issue, the decision matrix is represented as an nxn matrix. Where the a_{ij} elements are represented as a second kind Beta variables $B_{e2}(\alpha_i, \alpha_j)$ conformed by n parameters α_k shown in the matrix below. Note that the elements in the main diagonal must be by definition deterministic values equal to one. The vector with parameters α_k is defined as $\alpha = h \cdot v'$, where v' is the eigenvector of the matrix containing the $*a_{ij}$ values and h should be the minimum value that is computed in order to fulfill the condition (5.1) for each interval.

$$\begin{bmatrix} 1 & B_{e2}(\alpha_1,\alpha_2) & .. & .. & B_{e2}(\alpha_1,\alpha_n) \\ B_{e2}(\alpha_2,\alpha_1) & 1 & .. & .. & B_{e2}(\alpha_2,\alpha_n) \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ B_{e2}(\alpha_n,\alpha_1) & B_{e2}(\alpha_n,\alpha_1) & .. & .. & 1 \end{bmatrix}$$

Before calculating the probability to know which candidate network will be the best, the global priority vector of the alternatives should follow a Dirichlet distribution [4]. For this case, suppose that each node l in the tree has n descendants with parameters $\alpha_1, \alpha_2, ..., \alpha_n$ and each descendant m of node l has other k children with parameters $\alpha, \alpha_{m2}, ..., \alpha_{mk}$ to make the global priority vector follow a Dirichlet distribution with respect to node l, so condition (5.2) is fulfilled.

$$\sum_{h=1}^{k} \alpha_{mh} = \alpha_m; \vee_m = 1, 2, ..., n \tag{5.2}$$

Therefore to modify the parameters and make them respect to (5.2) [4], the new parameters should be defined by (5.3):

$$\alpha'_{mh} = \frac{\alpha_m}{\sum_{j=1}^{k} \alpha_{mj}} \cdot \alpha_{mh} \tag{5.3}$$

Now the global priority vector is Dirichlet distributed with parameters $\alpha_1, \alpha_2, ..., \alpha_n$ n defined by (5.4), where n is the number of available target networks and nf is the number of parameters used in the decision criteria.

$$\alpha'_h = \sum_{n=1}^{nf} \alpha_{mh} \tag{5.4}$$

Hence it is possible to calculate the probability that each target network has to be the best by (5.5) [4].

$$P[y_j = y_{[1]}] = 1 - \sum_{i=1}^{n} \sum_{x_i=0}^{\alpha'_i - 1} \frac{\Gamma(\alpha'_j + x_i)}{\Gamma(\alpha'_j) x_i!} (\frac{1}{2})^{\alpha'_j + x_i} +$$

$$+ \sum_{h=2}^{n-1} [(-1)^h \sum_{I(i_h)} \sum_{x_{i1-1}}^{\alpha'_{i1}-1} \sum_{x_{i2-1}}^{\alpha'_{i2}-1} \cdots \sum_{x_{ih}-1}^{\alpha'_{ih}-1} \frac{\Gamma(\alpha^t_j + \sum_{l=1}^{h} x_{il})}{\Gamma(\alpha'_j) \prod_{l=1}^{h} x_{il}!} \times$$

$$\times (\frac{1}{h+1})^{\alpha'_j + \sum_{l=1}^{h} x_{il}}] \ (5.5)$$

Where $I(i_h)$ is the set of permutations of the h elements excluding the jth one.

The computed values for the probability of each target network to be the candidate which provides the best QoS for the mobile are shown in Table 5.7.

Table 5.7: New AHP probability indicators (Analytic Approach)

Weight	Network 1	Network 2
Goal	0.97	0.03

5.4 Consistency of the Ranking

For the last part of this work we consider a simulation approach for handling the uncertainty into the AHP matrix as it is proposed by Levary and Wan in [26] . Since the uncertainty in the AHP is affected by subjective parameters, the authors of [26] propose that it can be more suitable to treat this issue by a simulation approach rather than to attempt to develop an analytical solution. Therefore in order to obtain the ranking of the target networks we get a single value for each interval of judgments which was modeled as a second kind beta distribution from the AHP matrix shown below.

$$\begin{bmatrix} 1 & B_e(\alpha_1,\alpha_2) & .. & .. & B_e(\alpha_1,\alpha_n) \\ B_e(\alpha_2,\alpha_1) & 1 & .. & .. & B_e(\alpha_2,\alpha_n) \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ B_e(\alpha_n,\alpha_1) & B_e(\alpha_n,\alpha_2) & .. & .. & 1 \end{bmatrix}$$

A matrix which contains deterministic values is obtained. Furthermore the classical AHP method can be applied in order to obtain the ranking of the target networks. Therefore to obtain a consistent solution several iterations of the process must be performed. The values gathered by simulation are shown in Table 5.8.

Table 5.8: AHP global priority indicators (Simulation Approach)

Weight	Network 1	Network 2
Goal	0.55	0.45

5.5 Results

In this work, all the results were obtained by a symbolic computing (Matlab) tool following an analytical and a simulation approach as it was exposed before. We show three different cases to test the performance or our algorithm; these are all shown from Table 5.6 to Table 5.16. In the first case as it is observed in Table 5.6, the best network to handoff due to the decision criteria is Network 1. However this part of the solution only provides information regarding the ranking of the target networks without considering uncertainty derived by the different requirements for each application.

Hence the deterministic solution cannot model properly by itself the handoff decision problem when multiple communication sessions are involved. In the first case the difference in the ranking of the target networks is small. Although the difference within the scores can be significantly smaller. As it is show in the second case in Table 5.10, this difference is near to zero. Hence it should be almost impossible for the mobile node to decide which network to handoff. Furthermore the probabilistic extension of the AHP method should be applied for a complete solution when the deterministic solution cannot provide confidence in the decision as it is presented in these cases. As it is observed in Table 5.7 and 5.9 respectively, the results show that when uncertainty regarding the different QoS requirements is incorporated in the decision process; a new index can be gathered to increase the level of confidence. This new index provides the mobile with the probability of the target network to be the best network to handover. Hence a more accurate decision can be made by the mobile node. For the third case we present, the information provided by the ranking of the networks is quite enough to make the decision. As it is show in Table 5.14, Network 2 is preferred. However the index obtained by the AHP probabilistic extension will be helpful to increase the grade of confidence Table 5.15. In the last part of this work, a simulation approach has been performed. The corresponding results are shown in Tables 5.8, 5.12 and 5.16. Simulating can be useful for comparison in order to observe the correct performance of our the method. However this approach provides similar results to the classical AHP method. In the case when the scores of the candidate networks are similar this method does not provide additional information for the handoff decision process.

Table 5.9: Measured values for each target network (case 2)

	Network 1	Network 2
Price	10	20
Bandwidth	0.7 ± 0.2	2.3 ± 0.15
Delay	10 ± 2	22 ± 4
PER	0.03 ± 0.009	0.01 ± 0.009
Jitter	35 ± 10	18 ± 4

Table 5.10: AHP average global priorities (case 2)

Weight	Network 1	Network 2
Goal	0.498	0.501
Price	0.666	0.333
Bandwidth	0.233	0.766
Delay	0.687	0.312
PER	0.25	0.75
Jitter	0.339	0.660

Table 5.11: New AHP probability indicators (Analytic approach, case 2)

Weight	Network 1	Network 2
Goal	0.309	0.701

Table 5.12: AHP global probability indicators (Simulation approach, case 2)

Weight	Network 1	Network 2
Goal	0.497	0.503

Table 5.13: Measured values for each target network (case 3)

	Network 1	Network 2
Price	18	20
Bandwidth (Mbps)	0.9 ± 0.2	2.3 ± 0.15
Delay (ms)	90 ± 10	8 ± 1
PER	0.03 ± 0.009	0.01 ± 0.009
Jitter (ms)	40 ± 6	10 ± 1

Table 5.14: AHP average global priorities (case 3)

Weight	Network 1	Network 2
Goal	0.295	0.704
Price	0.704	0.259
Bandwidth	0.465	0.5340
Delay	0.903	0.096
PER	0.250	0.750
Jitter	0.600	0.400

Table 5.15: New AHP probability indicators (Analytic approach, case 3)

Weight	Network 1	Network 2
Goal	≈ 0	≈ 1

Table 5.16: AHP global priorities (Simulation approach, case 3)

Weight	Network 1	Network 2
Goal	0.290	0.709

Chapter 6

Performance comparisons between different handoff decision algorithms

6.1 Simulation Scenario

In this section, we present results for the performance comparisons between three different handoff decision algorithms, which performance were measured by a symbolic computing tool (Matlab). The coverage area is assumed to be collocated within two networks: UMTS and a GPRS network. Four traffic classes defined by 3GPP in [29] are considered conversational, streaming, interactive and background. The mobile node carries simultaneously the combination of the following service classes: conversational and streaming, streaming and interactive, interactive and background. Each traffic class is associated with five different attributes: bandwidth, end-to-end delay, jitter, PER (Packet Error Rate) and price. For the simulation the connection life time is assumed to follow an exponential distribution [2]. The average connection lifetime $1/\mu$ is varied from 1 to 5 minutes. For each network i, the time between attribute values being changed also follows an exponential distribution with means equal to $\frac{1}{\gamma i}$. We use $\frac{1}{\gamma 1} = 4$ and $\frac{1}{\gamma 2} = 3$. The change in the value of the metrics evolve according to a Markov chain with the following state transition matrix [2]:

$$\begin{bmatrix} 0.5 & 0.5 & 0 & 0 & 0 \\ 0.25 & 0.5 & 0.25 & 0 & 0 \\ 0 & 0.25 & 0.5 & 0.25 & 0 \\ 0 & 0 & 0.25 & 0.5 & 0.25 \\ 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix}$$

For the bandwidth vector, we have: network 1 (UMTS) with [32 128 512 1024 2048] kbps network 2 (GPRS) with [21 64 107 128 149] kbps. For the delay vector we have: network 1 with [190 130 70 40 10] ms; network 2 with [185 135 85 35 10] ms. For the RSS values: network 1 with [70 55 40 25 15]; network 2 with [60 52 39 20 10]. The two networks have the same vectors for jitter, PER and price. The values for the jitter vector are: [3 5 7 9 11] msecs; the values for the PER vector are: [0.01 0.001 0.0001 0.00001 0.000001]; the values for the price vector are: [10 15 20 25 30] dlls. Each element of the vector represents the value of the attribute in the state of the chain and the matrix represents the transition probability.

The four traffic classes have different QoS requirements [31]. The AHP matrices for four traffic classes are shown in Table 6.1. The importance of the weights for each class is shown in Table 6.2. To account for this fact we have assigned different weights for the same attribute between different traffic classes. There are three schemes that will be considered to evaluate the performance in this work. All the results were obtained by a symbolic computing tool to compare the performance of the following schemes:

- *Basic RSS scheme*: The basic vertical handover algorithm only compares the RSS's values, no more criteria or decision algorithm is involved.

- *An individual optimization scheme based in the traditional AHP method, presented in Chapter 4*: This solution integrates an MIH QoS model, the AHP and cost functions to a fuzzy MADM handover decision algorithm.

- *Our proposed scheme, presented in Chapter 5*: The proposed algorithm integrates an MIH QoS model, the AHP and cost functions to a fuzzy MADM handover decision algorithm. Besides it integrates a framework for the decision making process which considers tradeoffs within the different services classes and the variant conditions of the target network.

Table 6.1: The AHP matrices for each traffic class

Conversational	Price	Bandwidth	Delay	PER	Jitter
Price	1	7	1	7	1
Bandwidth	$\frac{1}{7}$	1	$\frac{1}{7}$	1	$\frac{1}{7}$
Delay	1	7	1	7	1
PER	$\frac{1}{7}$	1	$\frac{1}{7}$	1	$\frac{1}{7}$
Jitter	1	7	1	7	1
Streaming	Price	Bandwidth	Delay	PER	Jitter
Price	1	1	3	7	1
Bandwidth	1	1	3	7	1
Delay	$\frac{1}{3}$	$\frac{1}{3}$	1	3	$\frac{1}{3}$
PER	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{3}$	1	$\frac{1}{7}$
Jitter	1	1	3	7	1
Interactive	Price	Bandwidth	Delay	PER	Jitter
Price	1	3	3	$\frac{1}{3}$	7
Bandwidth	$\frac{1}{3}$	1	1	$\frac{1}{5}$	5
Delay	$\frac{1}{3}$	1	1	$\frac{1}{5}$	5
PER	3	5	5	1	7
Jitter	$\frac{1}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{7}$	1
Background	Price	Bandwidth	Delay	PER	Jitter
Price	1	3	7	$\frac{1}{3}$	7
Bandwidth	$\frac{1}{3}$	1	5	$\frac{1}{5}$	5
Delay	$\frac{1}{7}$	$\frac{1}{5}$	1	$\frac{1}{9}$	1
PER	3	5	9	1	9
Jitter	$\frac{1}{7}$	$\frac{1}{5}$	1	$\frac{1}{9}$	1

Table 6.2: The importance of weights for each traffic class

Traffic Class	Price	Bandwidth	Delay	PER	Jitter
Conversational	0.3043	0.0435	0.3043	0.0435	0.3043
Streaming	0.2877	0.2877	0.0959	0.0411	0.2877
Interactive	0.2559	0.1117	0.1117	0.4871	0.0336
Background	0.2703	0.1375	0.0393	0.5137	0.0393

6.2 Results

Figure 6.1 shows the available bandwidth allocated under different vertical handoff decision algorithms, when the mobile node carries two different traffic classes with different QoS requirements and performs handoff to a new target network. The mean value is obtained by averaging the value from 4000 connections. The results in Figure 6.1 show that the mobile node receives the high average bandwidth when the new version of proposed AHP method is used for the decision making process. Furthermore from the results shown in Figure 6.2, it can be observed that the mobile node receives also the low end to end average delay when the new version of the proposed method is used. Therefore the mobile node handoff to the network which offers the more suitable QoS for both application sessions.

As it was exposed in Chapter 5 the main disadvantage of the traditional AHP method is that it cannot consider the tradeoffs between the different QoS requirements for both communications sessions. Hence it is not possible for this algorithm to take an accurate decision. In some cases, since the traditional AHP method is conceived as deterministic process it cannot decide which network is the more suitable network for both traffic classes. Therefore in this case the service is interrupted until the conditions of the network change. On the other hand for the comparison between the basic RSS scheme and the proposed algorithm, it is evident that the RSS scheme cannot perform correctly under vertical handover environments. Hence the RSS of different networks cannot be compared directly without considering the different QoS attributes for each target network. However we have considered the basic RSS scheme as a baseline for our proposed algorithm.

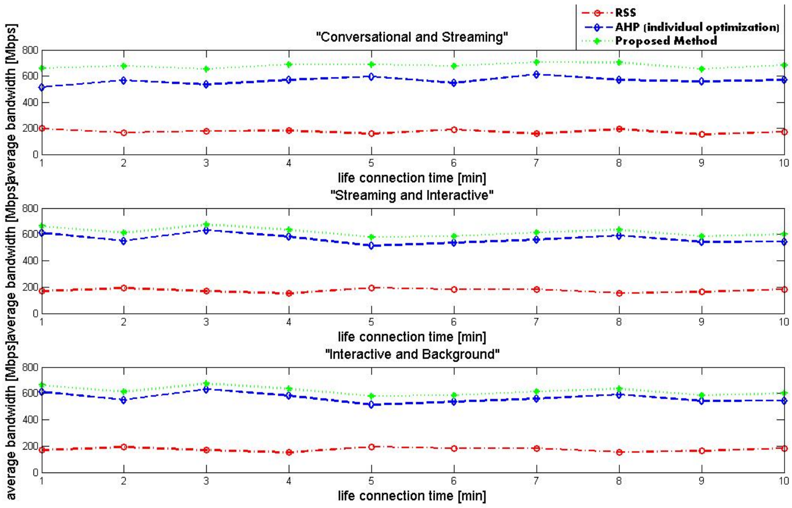

Figure 6.1: Average bandwidth vs life time connection

6.3 Sensitivity Analysis

In this section, we investigate the sensitivity of the three algorithms when the requirements of the candidate networks change. In the first case we propose a different vector of price for the GPRS network, since the price is

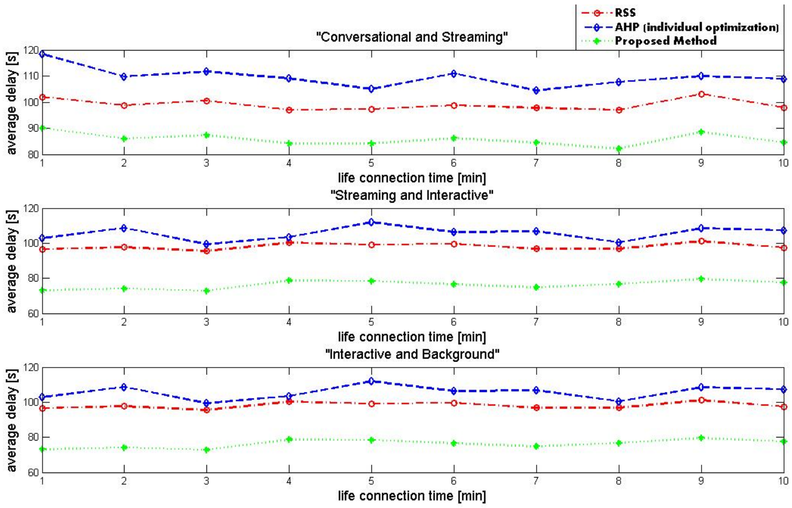

Figure 6.2: Average delay vs life time connection

a determinant factor for all the service classes shown in Table 6.2. We have changed the value of price in the GPRS network by the following vector: [30 35 40 45 50]. As we can see in Figures 6.3, 6.4 and 6.5, when the parameters of the network change our proposed model performs better. Since our method handoff to the network which provides the best QoS and the lower cost for the user.

For the last part of this section we proposed a different vector of jitter for the GPRS network [11 13 15 17 19]. However we should point out that jitter is not a determinant factor for all the traffic classes as it is shown in Table 6.2. The results observed in Figures 6.6, 6.7 and 6.8 show that when the jitter is a determinant factor for the combination within two traffic classes (streaming and conversational) the proposed algorithm offers suitable QoS requirements with low jitter. Therefore when the jitter is a determinant factor for only one service class (streaming and interactive) as it is shown in Figures 6.6, 6.7 and 6.8. The proposed algorithm establishes a tradeoff for the determinant parameters involved in the handoff decision process to provide the mobile with the more suitable QoS requirements for both application sessions. Furthermore when jitter is not a determinant factor for both communications sessions (interactive and background) involved in the decision process the proposed algorithm handoff to the network which offers the more suitable service requirements based in the determinant parameters, which in this case are bandwidth and delay. In such case it can be observed from Figure 6.8 that the average value of the jitter obtained when the mobile node carries interactive and background traffic is higher than in the other two cases exposed before. Since jitter is not a determinant factor as it was shown in Table 6.2 for these service classes.

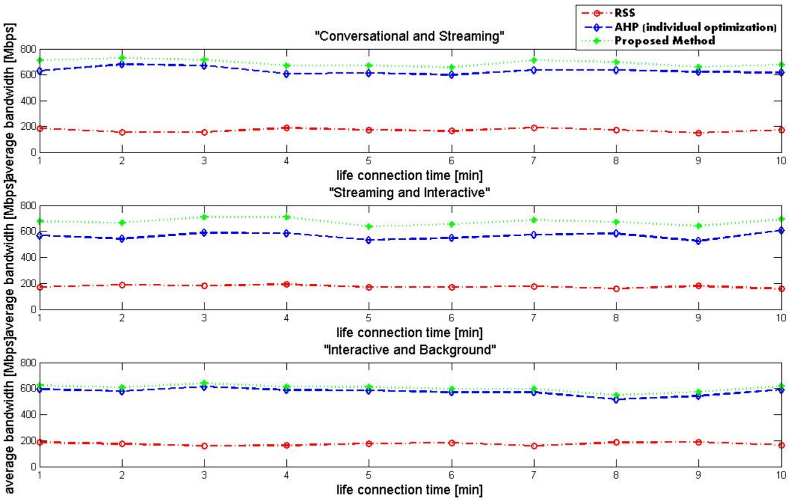

Figure 6.3: Average bandwidth vs life time connection

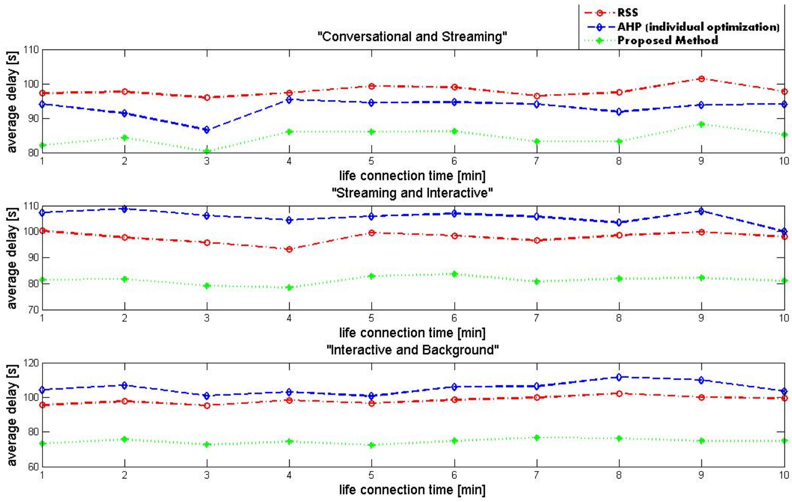

Figure 6.4: Average delay vs life time connection

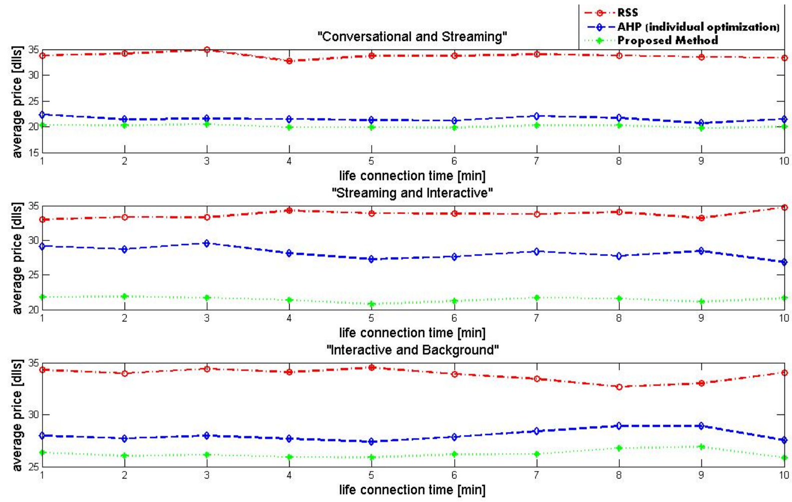

Figure 6.5: Average price vs life time connection

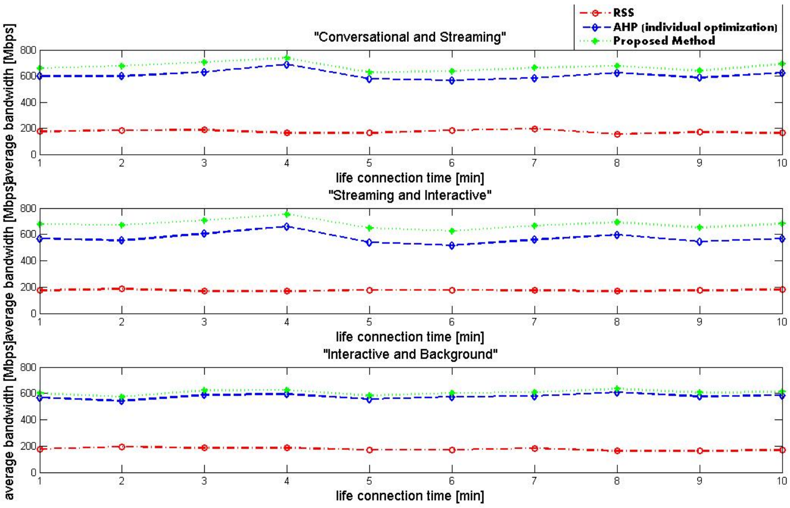

Figure 6.6: Average bandwidth vs life time connection

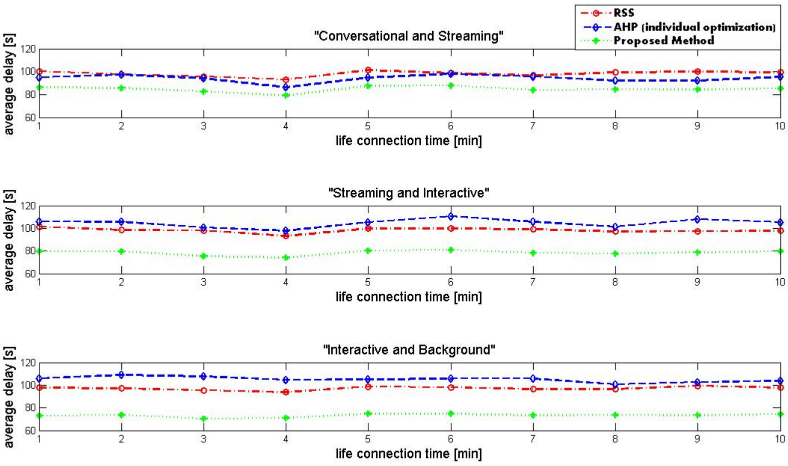

Figure 6.7: Average delay vs life time connection

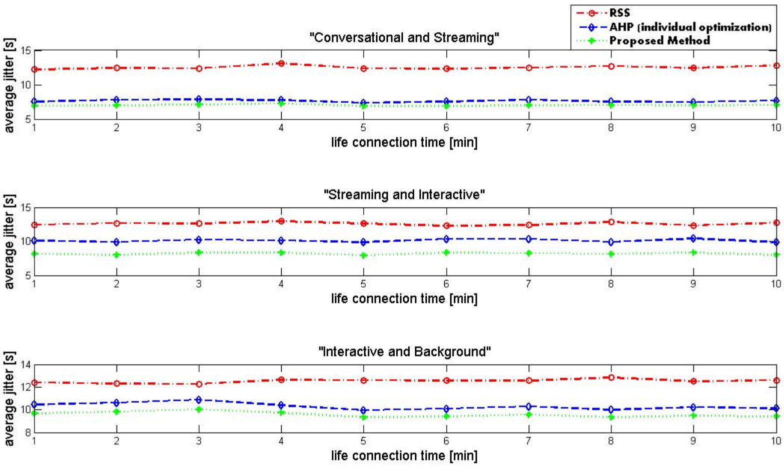

Figure 6.8: Average jitter vs life time connection

Chapter 7

Conclusions

In this work we have presented a novel solution for the problem when a mobile node carries multiple communication sessions with different QoS requirements and needs to execute handover to a new target network. To evaluate the performance of our algorithm, we have compared our proposed scheme with similar solutions. In order to do that, we have presented an extensive literature survey of the different schemes proposed for vertical handoff through heterogeneous networks. Since we have considered the handoff decision as an MADM problem, we have presented an extensive survey based on multicriteria decision making. In order to understand the principal concepts into the decision making process.

As we have exposed here the QoS requirements differ between traffic classes and tradeoffs between them should be considered to handoff to the more suitable network. Therefore we have proposed a new vertical handoff algorithm which considers the handoff through heterogeneous networks as group decision making problem. Furthermore we applied an extension of the classical AHP method, in order to provide the mobile node with two kinds of solutions: a deterministic solution based in the traditional AHP method and a probabilistic solution which considers the uncertainty in the judgments into the comparison matrix. The first solution provides the mobile node with information related to the ranking of the target networks and the second one the probability that this ranking remains stable considering the uncertainty into the comparison judgments. This method provides the mobile node with more parameters to make a more accurate decision when handoff is needed.

In order to test the performance of our algorithm we have considered traffic classes: conversational, streaming, interactive and background. We have shown that the proposed algorithm performs handoff to the network which provides the best QoS when the mobile node carries multiple communication sessions based in the determinant factors involved into the decision making process, since this algorithm considers the tradeoffs between different services classes. Furthermore it has been exposed that our proposed algorithm is sensible to the changes in the network conditions. In order to do that we have changed suddenly the network conditions. Therefore we have shown that our new method performs handoff to the more suitable network based in the determinant factors of each target network and in the QoS requirements for both communication sessions. Our future work will focus on proposing a method to reduce the ping-pong effect in heterogeneous networks based in the AHP process. Futhermore it will be useful to show simulations results based in the comparison of the proposed methods shown here by NS-2.

Bibliography

[1] Zhu Fang and McNair Janise. Optimizations for vertical handoff decision algorithms. In Proceedings of the Wireless Communications and Networking Conference, volume 2, pages 867-872, March 2004.

[2] Stevens-Navarro E. and Wong V. Comparison Between vertical handoff decision algorithms for heterogeneous wireless networks. In Proceedings of the 63rd IEEE Vehicular Technology Conference (VTC), volume 2, pages 947-951, 2006

[3] Wenhui Zhang. Handover decision using fuzzy MADM in heterogeneous networks. In Proceedings of the IEEE Wireless Communications and Networking Conference, volume 2, pages 653-658, March 2004.

[4] Manassero G, Semeraro Q and Tolio T. A new method to cope with decision makers uncertainty in the equipment selection process. In Proceedings of the CIRP Annals-Manufacturing Technology, volume 50, pages 389-392, 2004.

[5] Tawil Rami, Pujolle Guy and Demerjian Jacques. Distributed handoff decision scheme using MIH function for the fourth generation of wireless networks. In Proceedings of the Information and Communication Technologies: From Theory to Applications (ICTTA), pages 1-6, April 2008.

[6] Cacace Filipo and Vollero Luca. Managing mobility and adaptation in upcoming 802.21 enabled devices. International Conference on Mobile Computing and Networking. In Proceedings of the International Workshop on Wireless Mobile Applications and Services on WLAN hotspots, volume 7, pages 1-10, 2006.

[7] Hen Ling, Sun Tony and Chen Benny. A Smart Decision Model for Vertical Handoff. In Proceedings of the International Workshop on Wireless Internet and Reconfigurability (ANWIRE), January 2004.

[8] Song Qingyang and Jamalipour Abbas. A Network Selection Mechanism for Next Generation of Wireless Networks. In Proceedings of the IEEE

International Conference on Communications, volume 2, pages 1418-1422, May 2005.

[9] Stemm Mark and Katz Randy. Vertical handoffs in wireless overlay networks. In Proceedings of the Mobile Networks and Applications Conference, volume 3, pages 335-350, 1998.

[10] Yang Liu. Access network selection in a 4G networking environment. Master Thesis, University of Waterloo, Department of Electrical Engineering, 2008.

[11] Yoon Paul and Hwang Ching-Lai. ”Multiple Attribute Decision Making: An Introduction.” Sage Publications, 1995.

[12] Pardee E. S. Measurement and Evaluation of Transportation System Effectiveness RAND Memorandum RM-5869-DOT, 1969.

[13] Miller G.A. The magic number seven, plus or minus two. Psychological Review 63, 1956.

[14] Morris W. T. The Analysis on Management Decisions. Homewood, IL: Irwin, 1964.

[15] Rappaport Theodore. Wireless Communications Principles and Practice. Prentice Hall, second edition, pages 30-40, 2006.

[16] Goldsmith Andrea. Wireless Communications. Cambridge University Press, third edition, pages 1-26, 2005.

[17] Michael Steer. Beyond 3G. Microwave Magazine IEEE, volume 8, pages 76-82, Feb. 2007.

[18] T. L. Saaty. Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World. RWS Publications, 2008.

[19] Yang Shun-Fang, Wu Jung-Shyr and Huang Hsu-Hung. A vertical Media-Independent handover decision algorithm across Wi-Fi and WiMAX networks. In Proceedings of the Wireless and Optical Communications Networks (WOCN), pages 1-5, 2008.

[20] Wang Helen,Katz Randy and Giese Jochen. Policy-Eneabled handoffs across heterogeneous wireless networks. In Proceedings of the Second IEEE Workshop on Mobile Computing Systems and Applications (WMCSA), page 51, 1999.

[21] Zhu Fang,McNair Janise. Optimizations for vertical handoff decision algorithms. In Proceedings of the Wireless Communications and Networking (WCNC), volume 2, pages 867-872, March 2004.

[22] Chen Ling, Sun Tony and Chen Benny. A Smart Decision Model for Vertical Handoff. In Proceedings of the International Workshop on Wireless Internet and Reconfigurability (ANWIRE), January 2004.

[24] Xia Liu and Ling-ge Jiang. An intelligent vertical handoff algorithm in heterogeneous wireless networks. In Proceedings of International Conference on Neuronal Networks and Signal Processing, volume 10, pages 550-55, June 2008.

[23] Yang Kemeng and Gondal Iqbal. Combined SINR based vertical handoff algorithm for next generation of wireless networks. In Proceedings of the Global Telecommunications Conference (GLOBECOMM), pages 4483-4487, Nov. 2007.

[25] Zahir M. Sajjad. Incorporating the Uncertainty of Decision Judgments into the Analytic Hierarchy Process. In Proceedings of the European Journal of Operational Research, volume 53, pages 206-216, 1991.

[26] L. Reuven and W. Ke. A simulation approach for handling uncertainty in the analytic hierarchy process, In Proceedings of the European Journal of Operational Research, volume 106, pages 116-122, 2008.

[27] Stevens-Navarro E. and Wong V. Comparison Between vertical handoff decision algorithms for heterogeneous wireless networks. In Proceedings of the 63rd IEEE Vehicular Technology Conference (VTC), volume 2, pages 947-951, 2006.

[28] Wedley W. Combining qualitative and quantitative factors-an analytic hierarchy approach. In Proceedings of the Socio-Economic Planning Sciences, volume 24, pages 57-64, 1990.

[29] 3GPP, QoS Concepts and Architecture, TS 22.107 (v6.3.0), 2005.

[30] Oliva Antonio, Banchs Albert, Soto Ignacio. An overview of IEEE 802.21: Media Independent Handover Services. In Proceedings of the Wireless Communications IEEE, volume 15, pages 96-103, 2008.

[31] Vaca Rodrigo and Ramos Victor. A Vertical handoff algorithm which considers uncertainty during the decision making process. In Proceedings of the Wireless and Optical Communications Networks IEEE(WOCN), pages 1-6, Cairo Egypt, 2009.